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GRAVURES & HIGHLIGHTS OF THE YEAR

《Selection process of gravures and highlights》

Gravures and highlights will be selected in two-steps process. In the first step, referee will recommend manuscript for gravure or highlight. With the above recommendation, the editors will then give secondary recommendation.

After the following 1 and 2 are comprehensively considered, the editor-in-chief will draft a manuscript idea which will be thoroughly discussed by the editors for the final decision:

1. Approval based on the editor's judgement as an expert/non-expert in the field (thereby agreeing with the referee's recommendation)
2. Additional recommendation based on the editor's expertise.

Decay properties of ^{266}Bh and ^{262}Db produced in the ^{248}Cm + ^{23}Na reaction – Further confirmation of the ^{278}113 decay chain –

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$$\left[\begin{array}{l} ^{266}\text{Bh, } ^{262}\text{Db, } \alpha\text{-decay, spontaneous fission, gas-filled recoil ion separator, position-sensitive} \\ \text{focal plane detector} \end{array} \right]$$

A nuclide, ^{266}Bh, is the great-granddaughter of ^{278}113 that is produced in the ^{209}Bi + ^{70}Zn reaction[1,2]. Thus far, only five atoms have been assigned to ^{266}Bh by direct production[3,4] partly because of the small production cross section and of the difficulty in finding proper target/beam combinations. Most of the heaviest odd-odd nuclei exhibit rather complicated decay properties. Therefore, it is difficult to obtain a clear assignment of heavy odd-odd nuclides such as ^{266}Bh. In the present work, we performed an experiment with the aim of obtaining an unambiguous assignment of ^{266}Bh by a genetic link. The main purpose of this work is to provide further confirmation of the production and identification of the isotope ^{278}113. For this purpose, we used a gas-filled recoil ion separator (GARIS) coupled to a position-sensitive focal plane detector (PSD). ^{266}Bh was produced for the first time in the ^{248}Cm + ^{23}Na reaction.

The experiment was performed at the RIKEN Linear Accelerator (RILAC) Facility. A schematic view of the experimental setup is shown in Fig. 1. A photo picture of GARIS is shown in Fig. 2

A ^{248}Cm$_2$O$_3$ target having a thickness of 350 μg/cm^2 was prepared by electrodeposition onto a titanium backing foil (0.91 mg/cm^2). Six pieces of the target were mounted on a rotating wheel having a diameter of 10 cm. During irradiation, the wheel was rotated at 1000 rpm.

A ^{23}Na beam was extracted from RILAC. Beam energies of 126, 130 and 132 MeV were used. The corresponding beam energies at the middle of the target were 121, 124 and 126 MeV respectively. The ^{23}Na beam had a pulsed structure. All the measurements

were performed only in the beam OFF period. The typical beam intensity was 1 particle-μA on average, and it was 4.4 particle-μA in the beam ON period.

GARIS was used to collect evaporation residues (ERs) and separate them from the beam particles and other unwanted charged particles. GARIS was filled with helium gas at a pressure of 33 Pa. The Bρ of GARIS was set at 2.07 Tm for beam energies of 132 and 130 MeV to maximize the yield of ^{266}Bh. At beam energies of 126 MeV and a part of 132 MeV, Bρ was set at 2.19 Tm to reduce the counting rate of the focal plane detector to one half.

ERs were transported to the focal plane of GARIS where the PSD was set. The arrangement of the focal plane detector is shown in Fig. 1.

An example of a singles spectrum is shown in Fig. 3. The spectrum was obtained from one strip in one run with a beam dose of 3.1×10^{17}. In the energy region below 8 MeV, α lines from long-lived transfer products are observed, while in the region from 8 to 12 MeV, only one event that was assigned to an α decay of ^{266}Bh was detected.

The reduction in the number of transfer products and target recoils at the focal plane, that is achieved by using the physical pre-separator, GARIS and the high spatial resolving power of the PSD, enables a low background α-SF correlation measurements. The α-SF correlation measurement would be difficult to perform using only the gas-jet technique.

Other experimental details are described in the original paper. We performed offline analyses to search for mother-daughter correlations, i.e. α-α and α-SF events, based on the position in PSD, energy, and time difference.

We have assigned total of 32 correlations to true ones. Four of the events are α_1-α_2-α_3 correlations, one is an α_1-α_2-SF, nine are α_1-α_2 and eighteen are α_1-SF correlations. The maximum correlation time was set to 300 s.

A two-dimensional representation of the time- and position-correlated events is shown in Fig. 4. The horizontal and vertical axes represent the mother and daughter energy, respectively. The lower and upper panels (Figs. 4-a and 4-b) show the α-α and α-SF correlations, respectively.

The excitation energies of the compound nucleus,

^{271}Bh, at the middle of the target were calculated to be 44.4, 48.1 and 49.9 MeV for beam energies of 126, 130 and 132 MeV, respectively, by using a theoretical mass for ^{271}Bh[5]. The energies were selected to maximize the $5n$ evaporation channel in the ^{248}Cm + ^{23}Na reaction. Because the ER cross sections of these asymmetric reactions in the heaviest region exhibit a broad peaks around the optimum energies that produce the maximum yields, the isotope ^{267}Bh, which is a product of the $4n$ evaporation channel of the reaction, could be produced in considerable amounts, especially at lower excitation energies. We focused on these two isotopes in the analyses. The direct productions of ^{262}Db and ^{263}Db were not considered because of the reaction in the sub-barrier energy region.

α-α correlations

In the correlations shown in Fig. 4-a, eight points are plotted in Group C. The mother energies of these events range from 8.40 to 8.74 MeV, and those of the corresponding daughters range from 8.57 to 8.80 MeV. We assigned these events to the ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$ decay. The obtained $T_{1/2}$ in this work agrees very well with the adopted value[6]. It should be noted that the α energies obtained in this work are approximately 40–60 keV higher than the adopted energies[6]. This is most probably attributable to the summing of α-energy and a conversion electron or γ-ray energy, which is emitted simultaneously with the α-decay in the cases of odd and odd-odd nuclei[7].

Because of a shift in energy and the limited energy resolution caused by the summing effect, one event in Group C could be assigned to the decay of ^{263}Db $\rightarrow$ ^{259}Lr $\rightarrow$ as well as that of ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$, referring the reported half-life and α-decay energy of ^{263}Db[8] and those of ^{259}Lr[9], respectively.

Three of the eight correlations in Group C are the second part (α_2-α_3) of the triple correlations (α_1-α_2-α_3). All the preceding correlations (α_1-α_2) are in Group A, as shown in Fig. 4-a, along with four additional α_1-α_2 correlations. Because of the genetic correlation to the ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$ decay, these three triple correlation events in Group A are conclusively identified as the correlations of ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$ decays. The other four correlations are identified as those of the ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ decay or the ^{266}Bh $\rightarrow$ (^{262}Db $\rightarrow$ missing) ^{258}Lr $\rightarrow$ decay partly because the daughter energies agree well with the adopted decay energies of ^{262}Db and ^{258}Lr considering the above mentioned summing effect. The mean time differences between the α_1 and α_2 decays of the seven correlations in this group are calculated to be $34 \, ^{+20}_{-10}$ s. The corresponding $T_{1/2}$ is $24 \, ^{+14}_{-7}$ s. This value is attributable to a mixture of the ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ and ^{266}Bh $\rightarrow$ (^{262}Db $\rightarrow$) ^{258}Lr $\rightarrow$ decays. Including this mixture effect, the value agrees well with the adopted half-lives

of ^{262}Db and ^{258}Lr. The observed α-decay energies of ^{266}Bh range from 9.05 to 9.23 MeV. The correlations observed and assigned here agree well with those reported by Wilk et $al.$[3] and Qin et $al.$[4].

One α_1-α_2 correlation of the triple α correlation exists in Group B, as shown in Fig. 4-a. The corresponding α_2-α_3 correlation exists in Group C, suggesting that the correlations in Group B also correspond to the decay ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$. The energies of α_2 and α_3 agree well with the reported values for ^{262}Db and ^{258}Lr mentioned above. The observed α energy of ^{266}Bh assigned here is 8.83 MeV. Although the value just coincides with the decay energy of ^{267}Bh reported by Wilk et $al.$[3], because of the observed decay characteristics, we assigned the correlated event to the decay of ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$.

One additional correlation exists in Group B, as shown in Fig. 4-a. This could be also assigned to the decay of ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$ ^{258}Lr $\rightarrow$ because of the similarity with the energies and decay times of the correlation assigned above. However, based on the α_1-α_2 correlation analysis, assignment to the decay of ^{267}Bh $\rightarrow$ (^{263}Db $\rightarrow$) ^{259}Lr $\rightarrow$ is also possible if the summing effect is considered. Therefore, this correlation could not be assigned conclusively.

α_1-α_2 of one α_1-α_2-SF triple correlation is classified in a circle marked by D in Fig. 4-a. Here, the mother and daughter energies and the time difference between these decays, along with the followed SF decay, are fully consistent with the decay of ^{267}Bh $\rightarrow$ ^{263}Db $\rightarrow$ ^{259}Lr (SF)[3,9]. We then assign this correlation to the decay originating from ^{267}Bh.

α-SF correlations

The three correlated events in Group E in Fig. 4-b correspond to the α_1 energies of Group A (9.05–9.23 MeV). The corresponding half-life $T_{1/2}$ deduced from the three events agrees well with that of ^{262}Db. Therefore, we assign these correlated events to SF decays of ^{262}Db fed by 9.05–9.23 MeV α-decays of ^{266}Bh.

Eight correlations are observed in Group F in Fig. 4-b. No α-decays are observed in the α_1-α_2 correlations in this energy range, as shown in Fig. 4-a. The observed $T_{1/2}$ is slightly longer than the reported $T_{1/2}$ values of both ^{262}Db and ^{263}Db. Two α-decay events having an energy of around 8.96 MeV were reported by Qin et $al.$[4], and these are assigned to the decay of ^{266}Bh $\rightarrow$ ^{262}Db $\rightarrow$. However, their experimental setup was not sensitive to the α-SF correlations. The α-decays having an energy of around 8.96 MeV observed in the present work fed a state in the daughter that decays mainly by SF with $T_{1/2}$ of $59 \, ^{+32}_{-15}$ s. This α-decay could be tentatively assigned to the ^{266}Bh $\rightarrow$ ^{262}Db (SF) decay. However, the possibility of assignment to the ^{267}Bh $\rightarrow$ ^{263}Db (SF) decay could not be excluded. It should be noted that half the correlations were observed at the lowest incident energy.

One correlation exists in Group G, as shown in Fig. 4-b, along with the $\alpha_1(-\alpha_2)$-SF correlation that was assigned to the decay of ^{267}Bh $\to$ ^{263}Db $\to$ ^{259}Lr $\to$ in the present study. The α_1 energy and the SF decay time agree well with those of the correlation. Then, it is natural to assign this correlation to the decay of ^{267}Bh $\to$ ^{263}Db (SF) or ^{267}Bh $\to$ ^{263}Db $\to$ ^{259}Lr (SF). However, we have assigned one correlation having almost the same α_1 energy to the decay of ^{266}Bh (Group B in Fig. 4-a), suggesting that the correlation might still be assigned to the decay of ^{266}Bh.

Three correlations exist in Group H in Fig. 4-b. The deduced $T_{1/2}$ of the SF decay is 44^{+55}_{-15} s. One decay chain having a decay energy of 8.73 MeV was assigned to the decay of ^{267}Bh by Wilk $et\ al.$[3]. These correlations can possibly be assigned to the decay of ^{267}Bh $\to$ ^{263}Db (SF) or ^{267}Bh $\to$ (^{263}Db $\to$) ^{259}Lr (SF).

Two correlations exist in Group I in Fig. 4-b. The α-decay energy of the mother is approximately 8.43 MeV. One of these correlations is the α_2-SF part of the triple α_1-α_2-SF correlation. We have assigned this correlation to the decay of ^{267}Bh $\to$ ^{263}Db $\to$ ^{259}Lr (SF). The other correlation could also be the decay of ^{263}Db $\to$ ^{259}Lr (SF). We could tentatively assign these correlations to the decay mentioned above although the deduced SF half-life of ^{259}Lr is slightly longer than the adopted value.

Two correlations exist in Group J in Fig. 4-b. We could not assign these correlations.

9.05–9.23 MeV α decay of ^{266}Bh

An isotope of the 107th element, ^{266}Bh, which decays by α-emission with an energy ranging from 9.05 to 9.23 MeV, was conclusively identified by the present study. A state in the daughter nuclei ^{262}Db, fed by the α-decay, decays by α-emission and SF. In the observed decay chains of the isotope of the 113th element, ^{278}113, studied by the RIKEN group[1,2], one of the great-granddaughters decayed by α-emission with a decay energy of 9.08 MeV and decay time of 2.47 s, followed by SF. The assignment was based on an experimental result of the work done by Wilk $et\ al.$[3] that reported one atom of ^{266}Bh assigned by the sequential α decays ^{262}Db $\to$ ^{258}Lr $\to$. The present work provided further confirmation of the assignment of ^{266}Bh observed in a decay chain originating from ^{278}113 by demonstrating the observation of the same decay energy, as well as the observation of SF decays following the relevant α-decay of ^{266}Bh. A decay chain, which is attributed to be the one originating from the isotope ^{266}Bh obtained in the present work is shown in Fig. 5, together with the one from the isotope ^{278}113 produced in the ^{209}Bi + ^{70}Zn reaction.

Although a decay time analysis was performed in the macro beam OFF period, because of the small counting statistics, we could only state that the half-life is longer than 1 s.

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RIKEN Gas-filled Recoil Ion Separator GARIS
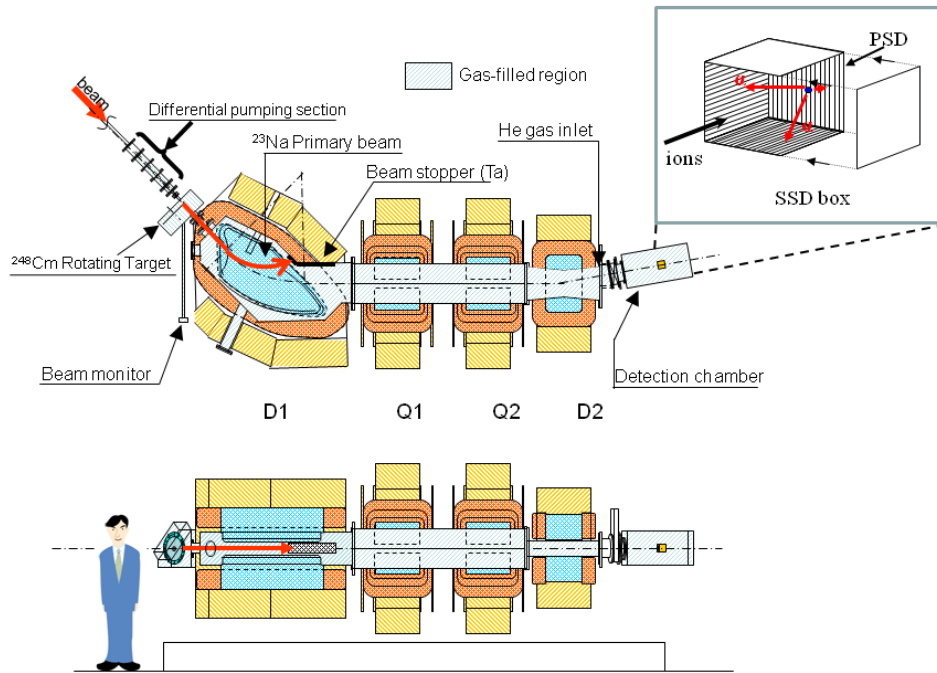
Fig. 1. Schematic view of the experimental setup.
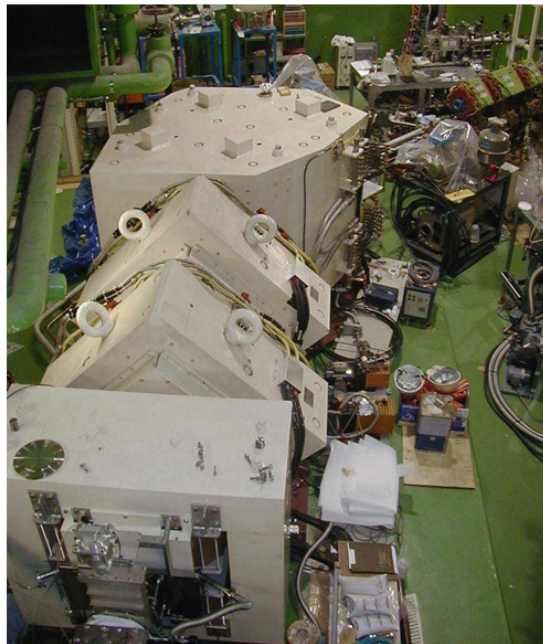
Fig. 2. Photo picture of GARIS.
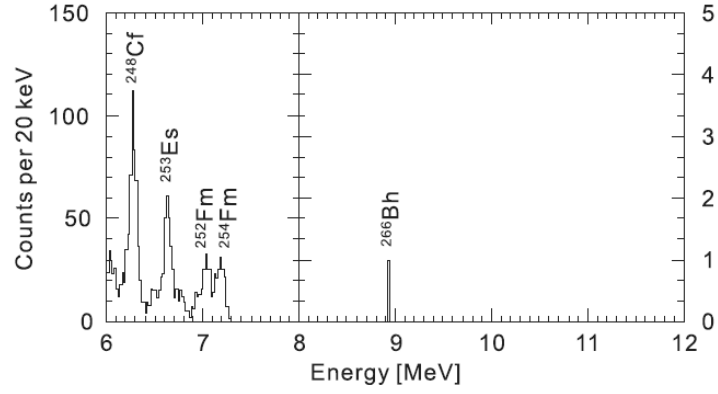
Fig. 3. Example of a singles spectrum. The 7th strip among 16 (0-15) in the PSD was used. The measurement time was 16.4 h for a beam dose of 3.1×10^{17}.
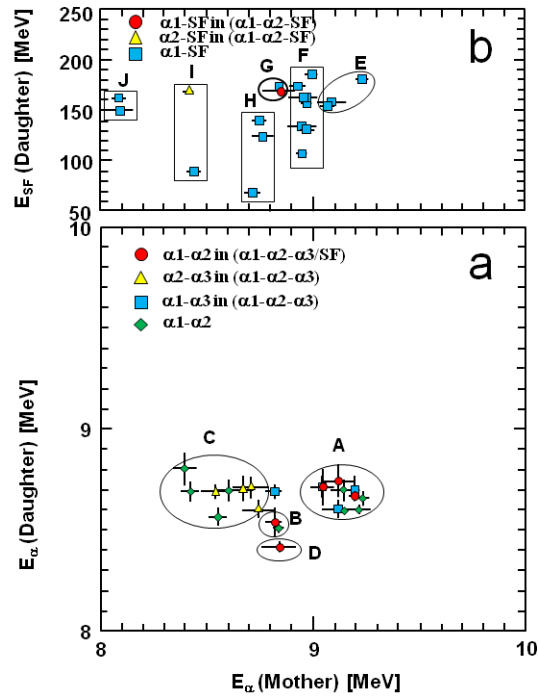
Fig. 4. Two-dimensional representation of time- and position-correlated events. The lower panel (a) shows the α-α correlations. The upper panel (b) shows the α-SF correlations. The time window was set to 300 s.
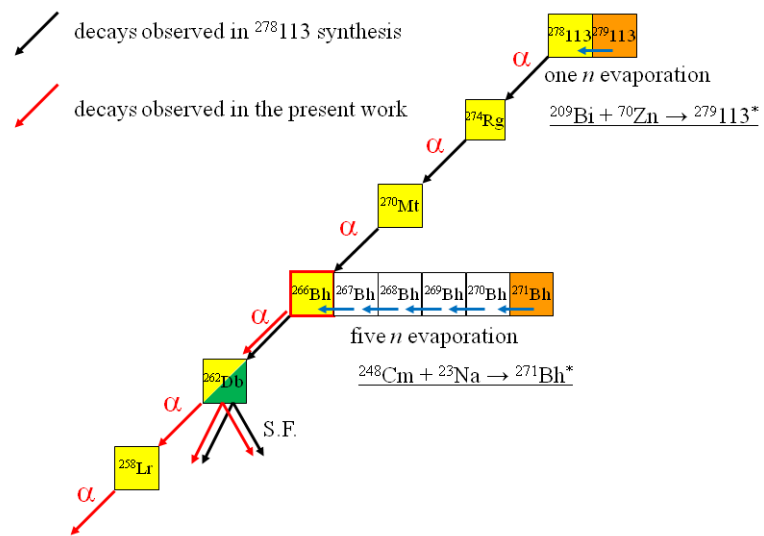
Fig. 5. A decay chain, which is attributed to be the one originating from the isotope ^{266}Bh obtained in the present work is shown, together with the one from the isotope ^{278}113 produced in the ^{209}Bi + ^{70}Zn reaction.

RF multipole devices play important roles in SLOWRI experiments: Hyperfine spectroscopy of $^7Be^+$ and new type of ion crystals in an RF octupole ion trap (PP. 18 and 230)

SLOWRI Collaboration

Developments of a universal slow RI-beam facility (SLOWRI) are in progress. At the prototype SLOWRI, radioactive Beryllium ions provided from the projectile fragment separator RIPS at ≈1 GeV were decelerated by an energy degrader and RF ion guide gas cell and trapped in a linear RF quadrupole ion trap. They were further cooled by laser radiation down to 1 μeV. This large kinetic energy reduction, a factor of 10^{-15}, allowed for precision hyperfine structure spectroscopy (Fig. 1).

In this experiment, one of the key devices is an RF octupole ion beam guide made of carbon fiber reinforced plastic (Carbon-OPIG) (Fig. 2). This device transports slow ions extracted from an RF-carpet towards an ion trap through five differential pumping sections, from 1 mbar to 10^{-9} mbar.
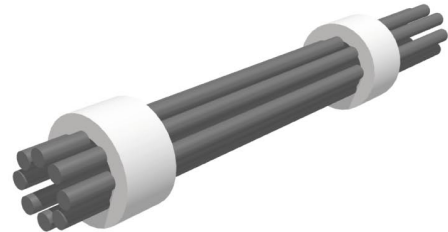
Fig. 2. Carbon-OPIG. Transverse DC electric field due to resistive rods transports ions even in 1 mbar pressure region.

Fig. 3. Linear RF octupole ion trap. High order multipole field produces large quasi-field free region in the middle of the trap.
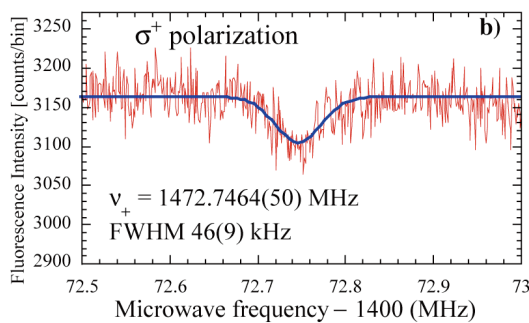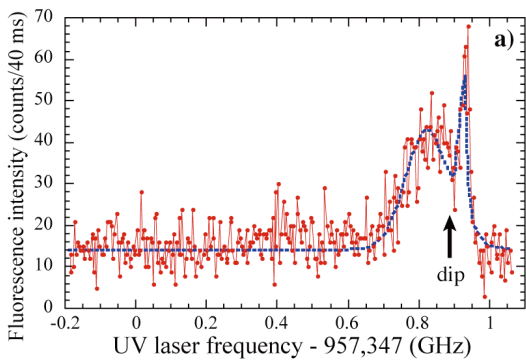
Fig. 1. Laser cooling spectrum (a) and microwave resonance spectrum (b) of $^7Be^+$.

A linear RF octupole ion trap (Fig. 3) was also tested off-line with Ca^+ ions at Sophia university. Due to the unique pseudo potential form in the octupole trap, ion Coulomb crystals with large concentric shells containing large number of ions were observed for the first time.
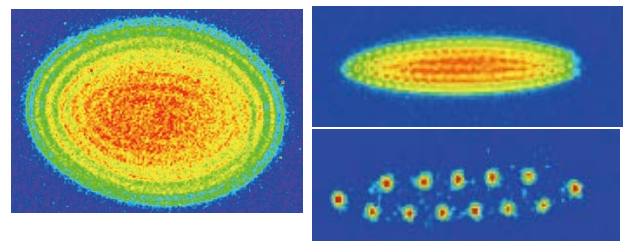
Fig. 4. Observed ion crystal images in the trap. Different type of crystals were formed depending on the trap conditions. A small potential hill at the center of the trap due to field penetration from the axial trapping potential produced large concentric shell structures.

Discovery of 20 new isotopes by in-flight fission of 345MeV/u ²³⁸U

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A new-isotope-search experiment has been performed by using the reaction of ²³⁸U (345MeV/u) +Be and Pb. Almost 20 isotopes were newly identified owing to significant improvement in the intensity and stability of the primary ²³⁸U beam after the last new-isotope-search in 2007.[1)]

The ²³⁸U beam accelerated up to 345 MeV/u by using RILAC-RRC-fRC-IRC-SRC was irradiated onto production targets and produced isotopes were collected and selected at the first stage of the BigRIPS. New isotopes with a wide range of A and Z were covered by three measurements with the BigRIPS settings optimized for isotopes with Z=20~36 (G1), Z=37~46(G2) and Z=47~54(G3). For each group, the target and Bρ were determined by Monte-Carlo simulation of LISE++.[2)] The determined targets were Be 5.1 mm for G1, Be 3.0 mm for G2 and Pb 0.95 mm for G3. For G3 a 0.3 mm Al stripper was also located after the target to increase fully stripped isotopes. The Bρ values are 7.902 Tm for G1, 7.931 Tm for G2, and 7.706 Tm for G3. Al degraders (1.29 mm for G1, 2.18 mm for G2, 2.56 mm for G3) were located at F1 to eliminate unwanted isotopes and reduce the total trigger rate.

Particle identification (PID) was performed at the second stage of the BigRIPS using PPACs at F3, F5 and F7, plastic scintillators at F3 and F7 and an ion chamber at F7. To confirm PID we also measured γ-rays from known isomers (⁹⁵Kr for G1 and G2 and ¹³⁶Sb for G3) using Ge detecto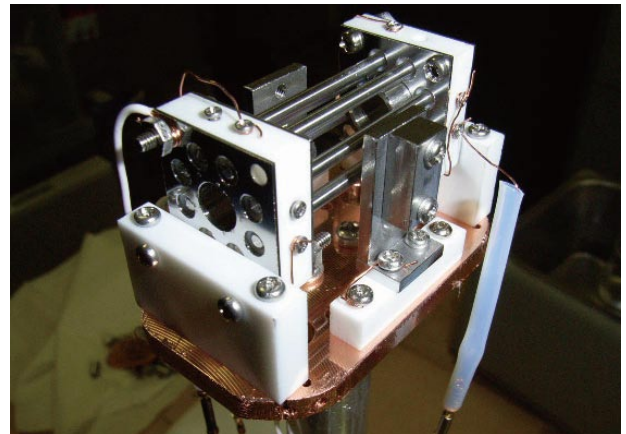rs located at F11 in the ZeroDegree spectrometer. For G3 only an Al degrader was inserted at F5 to cut hydrogen-like ions produced in the degrader at the first stage.

Figure 1a~c shows preliminary result of A/Q vs. Z plots for G1, G2 and G3. Three isotopes in G1(⁸¹Cu, ⁸⁴Zn, ⁸⁷Ga), 14 isotopes in G2(¹⁰³Rb, ¹⁰⁶Sr, ¹¹¹Zr, ¹¹⁴Nb, ¹¹⁶,¹¹⁷Mo, ¹¹⁹Tc, ¹²¹,¹²²Ru, ¹²³,¹²⁴,¹²⁵Rh, ¹²⁷,¹²⁸Pd) and 3 isotopes in G3 (¹³⁸Sn, ¹⁴⁰Sb, ¹⁴⁵I) can be clearly seen. Detailed analysis is in progress.

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*7 Institute of Physics, University of Tsukuba
*8 Department of Physics, Niigata University
*9 Physics Department, Western Michigan University
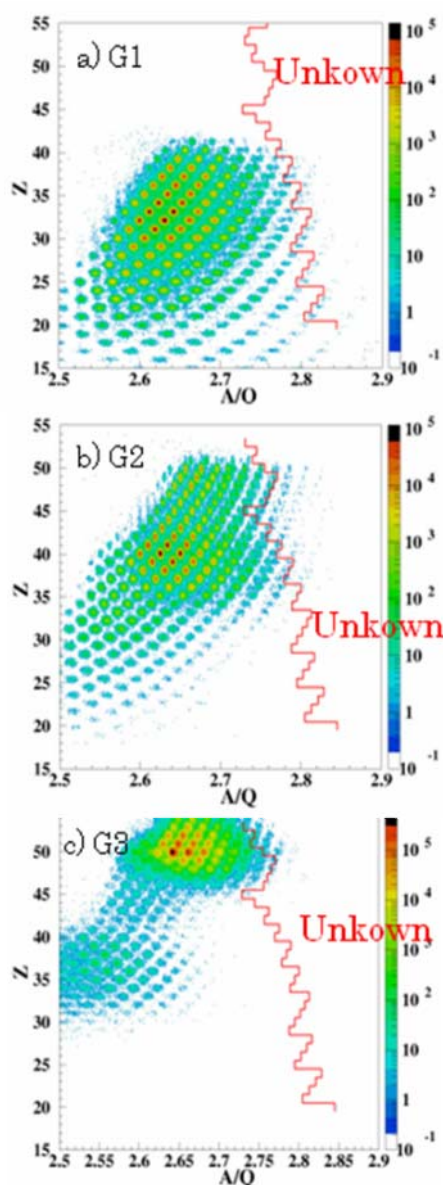*10 Michigan State University (MSU)
*11 Argonne National Laboratory (ANL)

Figure1. A/Q vs Z polts. a) for G1, b) for G2 and c) for G3

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Status of the RIKEN 28GHz Superconducting ECR ion source

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M. Komiyama, M. Kase, A. Goto, O. Kamigaito, and Y. Yano

Since the middle of the 1990s, RIKEN has been constructing a new accelerator facility called the Radio Isotope Beam Factory (RIBF)[1] and a 345MeV/u U beam was successfully produced in 2007. However, to meet the requirements of the RIBF project (primary beam intensity of 1 pμA on target), we still need to increase the beam intensity of heavy ions. For this reason, we began construction of a new superconducting ECR ion source (SC-ECRIS) with an operational frequency of 28 GHz in 2007.

Before designing the ECRIS, we intensively studied effects of the key components of ECRIS (magnetic field, RF power, etc,) on plasma conditions and beam intensity. In the 1990s, it was found that a high mirror ratio of magnetic field gives the increase of beam intensity for higher charge states of heavy ion (High B mode operation).[2] This is mainly due to a strong confinement of plasma. Since we observed in 2001 that the minimum strength of mirror magnetic field (B_{min}) strongly affects the beam intensity,[3] we have systematically studied this effect. In this study, we observed that an optimum B_{min} ((B_{min})$_{opt}$) exists for maximizing the beam intensity and it is almost constant (0.7~0.9B_{ecr}).[4] To investigate the mechanism, we used the laser ablation technique to obtain important plasma parameters (electron density, electron temperature and ion confinement time)[5] and observed that B_{min} strongly affects microwave absorption in the resonance zone.[6] In order to investigate the plasma chamber size effect on the beam intensity of highly charged heavy ions, we compared the beam intensity produced from several high performance ECRISs which have different chamber size. In this comparison, we recognized that the chamber diameter should be larger than 10 cm to produce an intense beam of highly charged U ions.[6]

Based on these considerations, we designed the new SC-ECRIS for the RIKEN RI beam factory project. To produce intense beam of U^{35+} ions, we will need to satisfy the following conditions

1) Magnetic field configuration: Maximum mirror magnetic filed strength on RF injection side (B_{inj})>3.5 T, maximum radial magnetic field strength (B_r)> 2 T, maximum magnetic field strength at beam extraction side(B_{ext})> 2 T, B_{min}~0~1 T.
2) Plasma chamber size: Diameter > 10 cm,
3) Microwave : Frequency, 28 GHz, power >10 kW (1 kW/L)
4) Size of resonance zone: There is no clear evidence of an ECR zone size effect on the beam intensity. If the size affects the beam intensity, we can increase the beam intensity by increasing size of the ECR zone. To clarify this effect, we adopted a special coil arrangement.

a)

b)
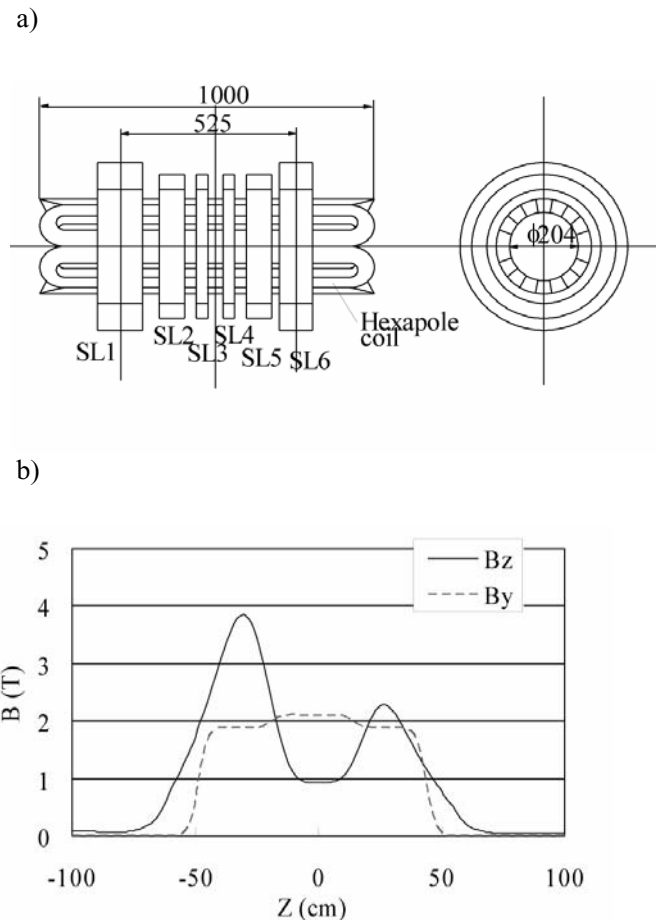
Fig. 1 a) Arrangement of the superconducting coil assembly. b)Axial (Bz) and radial (By) magnetic field strength

Figure 1a) shows the arrangement of the superconducting coil assembly. The coils are composed of six solenoid coils (SL1 ~ SL6) and one hexapole coil (HX). Figure 1b) shows the axial and radial magnetic field. Magnetic field strength was calculated by using the 3d-code "TOSCA". The peak fields on the RF injection side and beam extraction side are 3.8 T and 2 T, respectively. The minimum magnetic field can be changed from 0 T to 1 T. Four solenoid coils (SL2~ SL5) work to produce a flat magnetic field in the central region for increasing the size of the ECR surface. The detailed structure and excitation test are described in Ref. 7. Figure 2 shows the ECR zone size vs. B_{min}. Using this arrangement, we can produce large surface of ECR zone and change the surface size of the ECR zone without changing the field gradient.

Figure 3 shows a schematic drawing of the SC-ECR ion source. The inner diameter and length of the plasma chamber are 15 and 50 cm, respectively. The plasma chamber wall is made of Al to donate cold electrons to the

plasma and decrease plasma potential. It should be noted that Al is very resistant to plasma etching. A biased electrode is installed to obtain the same effect as that of the Al chamber wall. All the surfaces in contact with the plasma are water-cooled to minimizes the temperature effects caused by plasma and microwave heating at high microwave power.
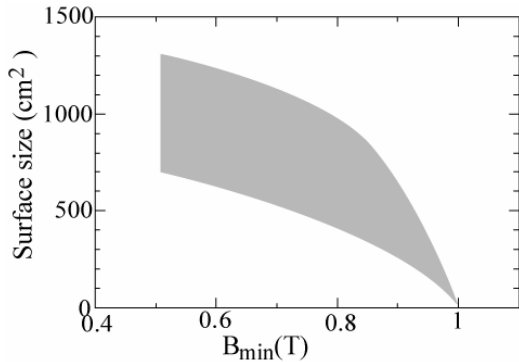
Fig. 2   ECR zone size vs. B_{min}

The expected total current from the ion source for production of 15 pμA of U^{35+} ion beam is higher than 10mA. Under this condition, we have to supply a very high extraction voltage (higher than 30 kV) to acheave good emittance (unnormarized emittance of ~150π mm・mrad) for matching the acceptance of the RFQ linac. The ion source will be equipped with a movable accel-decel extraction system not only to improve extraction conditions, but also to compensate for the space charge effect. After extraction at the maximum voltage of 40 kV, the solenoid coils are used to focus the beam. Design of the 90-degree analyzing magnet is based on the LBL magnet[8]. The vertical gap is 150 mm and bending radius is 510 mm. These devices are installed on the high voltage terminal (maximum terminal voltage; 100 kV). The U^{35+} beam (~130q keV) will be transported to the first acceleration tank of Riken heavy ion linac through new beam line[9]. By end of March, 2009, we will finish installing all devices (SC-ECRIS, analyzing magnet etc,) on the high voltage terminal and try to produce the first plasma with 18 GHz microwaves.

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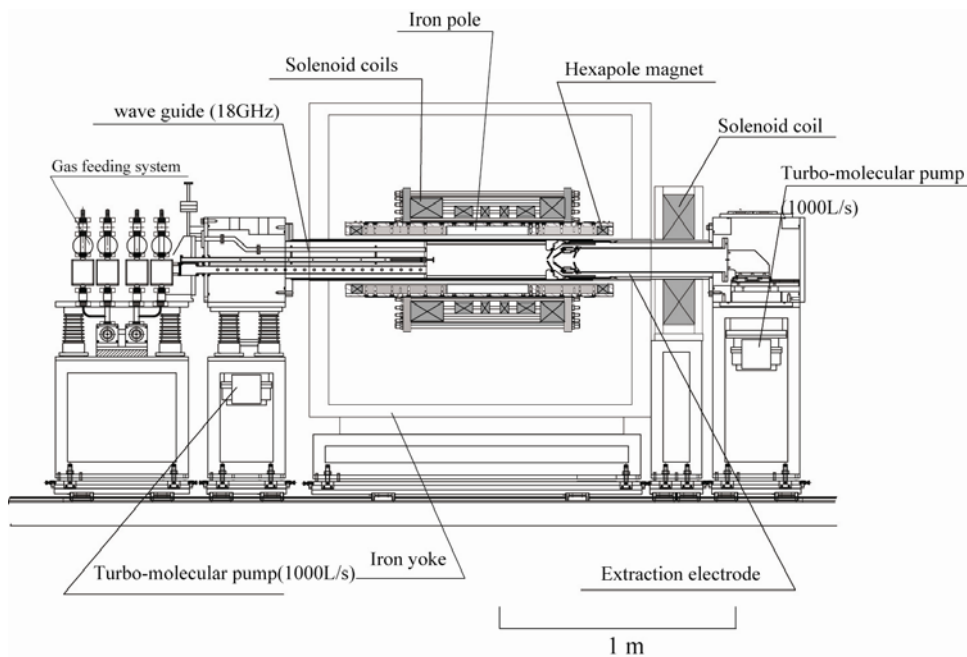
Fig.3. Schematic drawing of the RIKEN Sc-ECRIS

A new cultivar "Nishina Zaou" induced by heavy ion beam irradiation

S. Ishii[*1], Y. Hayashi, H. Ryuto[*2], N. Fukunishi, and T. Abe

Prunus lannesiana 'Gioiko' is the only Japanese ornamental cherry variety that has a double flower with 10 to 12 petals. The color of flower changes from pale green to light purple during blooming time. Recently, heavy ion beams are recognized as an effective mutagen for plant breeding. A broad spectrum and a high frequency of mutation induction by heavy ion beam have proved in the case of rose[1]. Some new cultivars of ornamental flowers induced by heavy ion treatment have been successfully developed and released to the market. In this report we describe the induction of a new cultivar of Japanese ornamental cherry using heavy ion beam irradiation.

The scions (approximately 150mm in length) of Gioiko were used for irradiation treatment. The doses of carbon beam irradiation ($^{12}C^{6+}$, 135MeV/u, LET 22.6keV/μm) were 10, 15 and 20Gy. The irradiated scions were grafted on the rootstock (*Prunus lannesiana* 'Viridis'). Survival rate, a period from grafting scions on the rootstock to the first bloom, flower phenotypes (petal color, petal number and size of flower) were observed.

The survival rate decreased according as the increase of doses (Fig.1). At 20Gy irradiation, no plant survived. A flower colour mutant was isolated at 10Gy irradiation (Fig.2). The colour of mutant flower was pale yellow at the beginning of blooming time and then changed to yellowish pink. The color of the rims of petals was whitish green. The flower diameter was 40-50mm, which was 1.5 times larger than that of the original variety. The petal number was 7-8. The period from grafting to the first bloom of mutant line was one year but 3years in original variety (Fig.3). Reduction of the period from grafting to the first bloom is useful character for both breeding and commercialization of the new cultivar. These characters of this mutant line

were confirmed to be stable in the following season. This new cultivar was named "Nishina Zaou" by Dr. Noyori; the president of RIKEN in 2007. Nishina Zaou was released to the market in Nov. 2008.
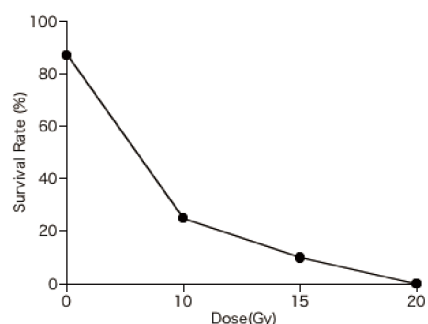
Fig. 1 Effect of C-ion irradiation on survival rate
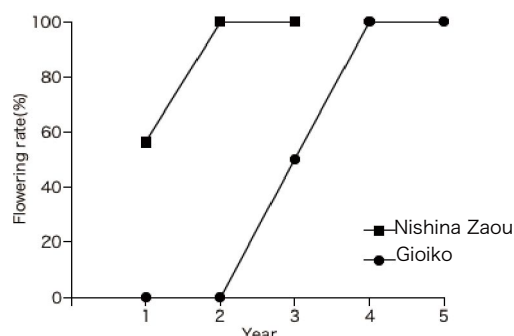
Fig. 3 Effect of C-ion irradiation on the period from grafting to the first bloom

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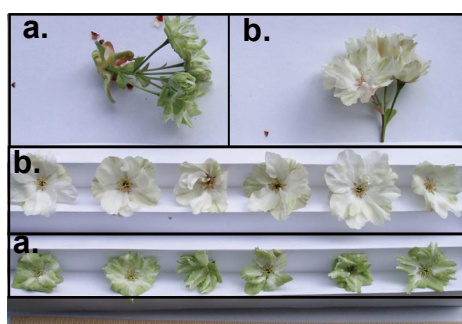
Fig. 2 Flower colour mutant.
a: Original flower (Gyoiko).　b: Mutated flower.
c: Nishina Zaou planted in RIKEN (Wako). The scion was grafted in 2007, and the flower bloomed in April 2008.

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Demonstration of electron scattering using the SCRIT prototype

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[SCRIT, elastic electron scattering, angular distribution]

We have continued SCRIT R&D studies at KSR this year. We have newly installed a large plastic scintillator for cosmic-ray rejection and an online luminosity monitoring system[1]. In this report, some progress we made this year are briefly presented.

Figure 1 shows electron energy spectra for the scattering angle of 40°. Figure 1a) and b) show those obtained the last year[2] and this year, respectively. The solid (dotted) line denotes the spectrum with (without) the Cs ion injection. Clear difference between those with and without Cs ions $80 \leq E_e \leq 120$ MeV are due to the elastic scattering events from the trapped Cs ions. The events above $E_e \geq 120$ MeV have been attributed to those due to cosmic rays. It is seen that the cosmic ray events are well suppressed in Fig.1b), which enables us to identify elastic events reliably.

Figure 2 shows the change of event rate of elastic scattering in the 60-ms trapping time, equivalently the time dependence of the luminosity. Since the electron beam current, ~ 80 mA, and its cross section are both almost constant, this figure shows the time dependence of the number of the trapped Cs ions on the electron beam. The line in the figure is a guide for the eye. One can conclude that the number of the trapped Cs ions decreases about 30 % during the trapping cycle.

Figure 3 denotes the angular distributions of the measured elastic scattering events already presented in Ref.[2]. The solid line in the figure represents a dis-

Fig. 2. Distribution of the elastic events as a function of the trapping time. The line is a guide for the eye.
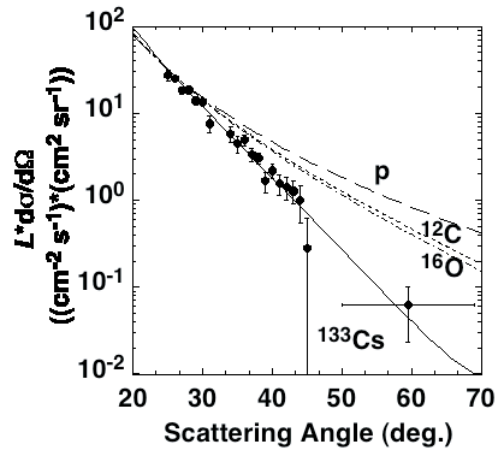
Fig. 3. The angular distribution of the elastic events. See the text for the lines.

torted wave calculation for elastic scattering off ^{133}Cs. The dashed (dotted, dot-dashed) line represents the angular distribution of the elastic scattering for proton (carbon and oxygen), which are normalized to the data at a scattering angle of 25°. They are considered to be the main components of the residula gases in the ring to focus on the difference in angular dependence such as H_2 and CO. The angular dependence clearly shows that the measured events are those of elastically scattered electrons from the trapped ^{133}Cs[3].

Fig. 1. The energy spectra for scattered electrons at $\theta=40°$ measured in the previous measurement[2], a), and for this year, b). The solid (dashed) line shows the spectrum with (without) the Cs ion.

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Production and decay properties of ^{263}Hs[†]

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$\left[^{263}\text{Hs, new isotope, hassium, GARIS} \right]$

A new neutron deficient hassium (Z=108) isotope of ^{263}Hs was identified via two different reactions of ^{206}Pb(^{58}Fe,n) and ^{208}Pb(^{56}Fe,n) by using the gas-filled recoil separator GARIS.

Projectiles of ^{58}Fe and ^{56}Fe with the charge state 13^+ were extracted from the 18-GHz ECR ion source and accelerated by RILAC (RIKEN Linear Accelerator). Beams of ^{58}Fe with 287.7 MeV and ^{56}Fe with 280.4 MeV were extracted from RILAC. Absolute accuracy of beam energy measurement was $\pm$ 0.3 MeV. The typical beam intensities on the target were 4.5×10^{12} s^{-1} for ^{58}Fe and 2.3×10^{12} s^{-1} for ^{56}Fe. The target was prepared by the vacuum evaporation of metallic ^{206}Pb and ^{208}Pb on a 30 μg/cm^2 carbon backing foil. The target thicknesses were 400 μg/cm^2 for ^{206}Pb (enrichment of 99.3%) and 440 μg/cm^2 for ^{208}Pb (enrichment of 98.4%). A thin carbon protection layer of approximately 10 μg/cm^2 covered the target surface on the downstream side. Sixteen targets were mounted on a ϕ30 cm wheel, which rotated at 3000 rpm, to withstand the irradiation of high intensity beams. The reaction products were separated in flight from the beams by GARIS, and were guided into a detector box installed at the focal plane of GARIS. The separator was filled with helium gas at a pressure of 86 Pa. The magnetic rigidity $B\rho$ was set to 2.05 Tm for ^{263}Hs measurement, which was estimated using empirical data.[1] The evaporation residue (ER) and its successive radioactive decays were measured by a system of time-of-flight (TOF) detectors and a silicon position-sensitive detector (PSD) array[2] installed at the focal plane of GARIS. Identification of the products was based on the genetic correlations of mother and daughter nuclei. The singles counting rate of the PSD at the typical beam intensity was approximately 5 cps. The main components of the signals were due to target recoils and scattered beam particles. The counting rate of the decay signals (anti-coincidence with timing counters) was approximately 0.3 cps.

During 25-h irradiation of ^{206}Pb with the ^{58}Fe beam and 46-h irradiation of ^{208}Pb with the ^{56}Fe beam, 8

decay chains and 1 decay chain, respectively, were observed. No spontaneous fission was detected in the measurements followed directly after the ER implantation in the PSD. The properties of decay events obtained by irradiation of ^{58}Fe on ^{206}Pb match well with those by irradiation of ^{56}Fe on ^{208}Pb. All decay chains were assigned to subsequent decays from ^{263}Hs. The decay data obtained in this work is summarized in Fig. 1. Three groups of α-decay energies for ^{263}Hs are identified. The mean α-decay energies for the 3 groups are 10.82, 10.55, and 10.37 MeV, respectively. The half-life of ^{263}Hs is determined to be $0.60^{+0.30}_{-0.15}$ ms. In this experiment, the total beam doses for ^{58}Fe and ^{56}Fe were 4.1×10^{17} ions and 6.2×10^{17} ions, respectively. The production cross sections corresponding to the 8 decay chains and 1 decay chain have been deduced to be 21^{+10}_{-8} pb and $1.6^{+3.7}_{-1.3}$ pb by assuming the transmission of the system to be 80%.

The details of this experiment have described elsewhere.[3,4]

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† Condensed from the article in J. Phys. Soc. Jap. **78**, 035003 (2009)
*1 Department of Physics, Tohoku University
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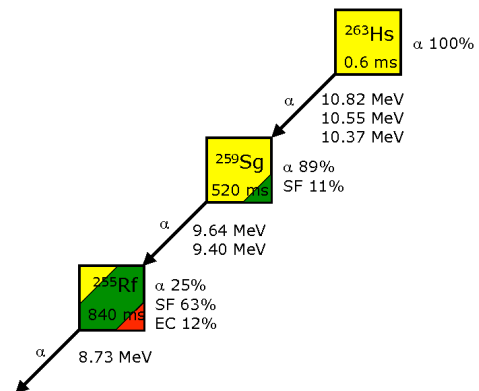*6 Department of Physics, Saitama University

Fig. 1. Summary of decay chains observed in irradiation of ^{206}Pb and ^{208}Pb targets with ^{58}Fe and ^{56}Fe projectiles. Measured energies, decay times, and branching ratio are indicated in the figure.

Precision optical transition measurements for ^{7,9,10,11}Be$^+$ ions

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[neutron halo, charge radius, laser spectroscopy]

We have developed an online ion trap for precision atomic spectroscopy where unstable Be ions are stored for a long time and laser-cooled down to a very low temperature[1,2]. This is an ideal condition to perform double resonance spectroscopy to determine the absolute optical transition energies to deduce the isotope shifts of the optical transitions. From the isotope shifts, we can systematically determine the nuclear charge radii of Be isotopes.

The finite mass and size of a nucleus influence the electron binding energies of an atom. In the case of light nuclei such as Be, the field shift due to the size of a nucleus is as small as 10 MHz, whereas the optical transition energy is about 10^9 MHz and the mass contribution is about 10^3 MHz. The determination of charge radii requires not only theoretical calculations for the mass shift and other effects, such as QED effects, with sufficiently high accuracies but also the relative accuracies of the measurements must be as high as 10^{-9}.

To measure the optical transition energy, we used the optical-optical double resonance (OODR) spectroscopy method[3]. In the cooling process, ions are optically pumped between the states $2\,^2S_{1/2}$(largest F) and $2\,^2P_{3/2}$ and strong laser-induced fluorescence is observed. If the optical pumping is imperfect, some fraction of the population remains in the other states. Under such a condition, if we use a weak probe laser resonant to the $2\,^2S_{1/2}$(smaller F)$-2\,^2P_{3/2}$ transition, a part of the population in the smaller F state is transferred to the larger F state. Then, an increase in the laser-induced fluorescence signal is observed. The cooling probe lasers alternately irradiated the trapped ions, using electro-optic modulators and polarizers to avoid the power broadening and shift effects. In this way, we can obtain a symmetric Lorentzian profile for the $2\,^2S_{1/2}-2\,^2P_{3/2}$ transition with a width close to the natural line width. The probe laser frequency was simultaneously measured by a clockwork optical femtosecond frequency comb (Menlo Systems FC1500)[4]. Then we can determine the absolute frequency of energy transitions with extremely high accuracy.

Typical OODR spectra are shown in Fig. 1 fitted with Lorentzian profiles to determined the res-

onance frequencies. Using the results compensated from the hyperfine splittings constant and the Zeeman splittings, the absolute transition frequencies in the $2\,^2S_{1/2} \rightarrow 2\,^2P_{3/2}$ transition of ^{7,9,11}Be$^+$ were obtained to be 957 347 372.2(1.6) MHz, 957 396 620.6(2.7) MHz and 957 428 168.9(2.5) MHz respectively. Although the same method is not applicable for the even-even nucleus ^{10}Be, we carefully measured the cooling transition at zero magnetic field and obtained a sharp symmetric spectrum (Fig. 1). From this spectrum, we determined the $S_{1/2} \rightarrow P_{3/2}$ transition energy of ^{10}Be$^+$ as 957 413 949.8(0.5) MHz. The uncertainties of these values are mainly due to poor statistics.
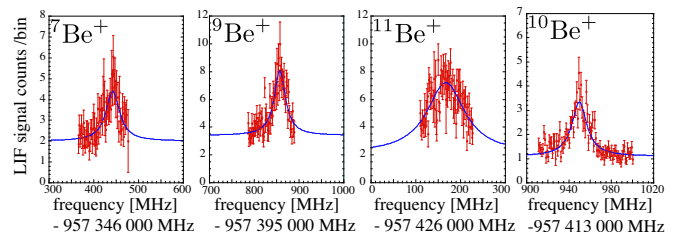
Fig. 1. OODR spectra of $2\,^2S_{1/2} \rightarrow 2\,^2P_{3/2}$ transition for ^{7,9,11}Be$^+$ and laser cooling spectrum for ^{10}Be$^+$.

The experiment is still in progress to achieve more accurate and reliable data. However, we preliminary evaluate the charge radii of Be isotopes as shown in Fig. 2.
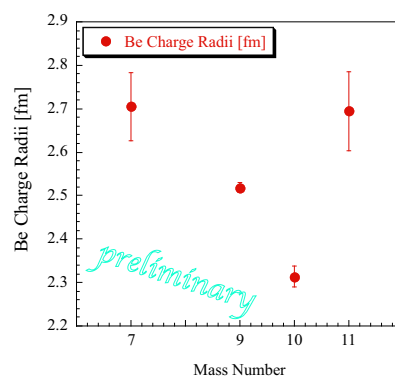
Fig. 2. Preliminary evaluated charge raii of Be isotopes.

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Observation of new neutron-rich short-lived isomers among fission products of 345 MeV/nucleon ^{238}U

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[In-flight fission, neutron-rich nuclei, short-lived isomer]

The BigRIPS separator provides intermediate energy radioactive isotopes (RI) that are identified event by event by their mass, A, and charge state, Q, in flight. In the 2008 search for new isotopes using in-flight fission of a 345 MeV/nucleon ^{238}U beam, the intensities of the cocktail RI beams were around or below 1 k particles/s. The situation has allowed us to observe isomeric decays of the products, whose halflives are around a microsecond, in the neutron-rich region far from stability. During the new isotope search, we observed more than ten new isomers in detecting γ rays gated on the isotopes which were identified by using the so-called particle identification plot of A/Q versus proton number. Of these, this report describes the isomeric states of the neutron-rich Br isotopes, ^{94}Br and ^{95}Br, which were one of the intense isomers observed.

The γ-rays emitted from the isomeric states were detected using three clover-type Ge detectors located at the end of the ZeroDegree spectrometer. To stop the Br beams close to the detectors, an aluminum stopper was installed at the end of the beam line. The thickness of the stopper, 8.1 g/cm^2, was chosen to stop almost all of the products in the new isotope search setting. The detail of the setup is described elsewhere. We accumulated the γ rays triggered by the particles with a 20 μs time window. The beam condition of the Br isotopes is shown in Table 1.

Figure 1 shows the γ-ray energy spectra observed for ^{94}Br and ^{95}Br. To reduce γ background due to beam irradiation, which appears as a prominent peak in the γ time spectrum, the events around the peak were excluded. We have observed two strong peaks at 91.7 and 202.3 keV for ^{94}Br and a strong peak at 537.9 keV for ^{95}Br. In the insets, the decay curves

gated by these γ rays are presented. In ^{94}Br, the preliminarily obtained halflives for the 91.7 and 202 keV γ rays are 713(71) ns and 655(46) ns, respectively. The agreement within the errors suggests that these γ rays come from an identical isomeric state. In ^{95}Br, a preliminary halflife of the 538 keV γ rays was obtained as $T_{1/2} = 4.0(12)$ μs. Further analysis is now in progress.
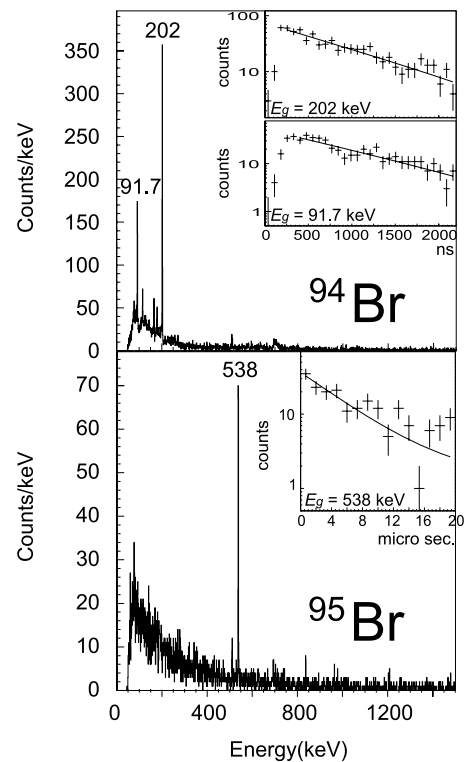
Fig. 1. γ-ray energy spectra for ^{94}Br and ^{95}Br

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*10   Michigan State University
*11   Argonne National Laboratory

Table 1. Beam condition for the Br isotopes.

	^{94}Br	^{95}Br
production target	Be 5 mm	
charge state	35(fully stripped)	
yield in stopper	2.1×10^5	4.0×10^4

α-Particle Condensation in ^{16}O Studied with a Full Four-Body Orthogonality Condition Model Calculation†

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[Nuclear structure, Cluster model, Alpha particle]

It is well established that α-clustering plays a very important role in the structure of light nuclei.[1,2] The importance of the α-cluster formation has also been discussed in infinite nuclear matter, where α-particle type condensation is expected at low density,[3] quite analogous to the recently realized Bose-Einstein condensation of bosonic atoms in magneto-optical traps.[4] Regarding α-particle condensation in finite nuclei, only the Hoyle state, i.e. the 0_2^+ state in ^{12}C has clearly been established thus far. Several past papers[2] and also more recent papers[5–7] have by now established beyond any doubt that the Hoyle state, only having about one third of saturation density, can be described, to good approximation, as a product state of three α-particles, condensed into the lowest mean field $0S$-orbit.[8,9]

In this short note we present a result of the exploration of the 4α condensate state by solving a full Orthogonality Condition Model (OCM) four-body equation of motion without any assumption with respect to the structure of the 4α system. Here we take the 4α OCM with Gaussian basis functions,[10] the model space of which is large enough to cover the 4α gas, the $\alpha+^{12}$C cluster, as well as the shell-model configurations. The OCM is extensively described in Ref. 11.

As a result of the calculations, we can reproduce the full spectrum of 0^+ states up to about 15 MeV, and tentatively make a one-to-one correspondence of those states with the six lowest 0^+ states of the experimental spectrum. In view of the complexity of the situation, the agreement is considered to be very satisfactory (see Fig. 1 in Ref. 12).

The 0^+ spectrum of ^{16}O up to about 15 MeV is now essentially understood, including the 4α condensate state. This is a remarkable improvement in our knowledge of the structure of ^{16}O. The structures of the 0_2^+ state at 6.05 MeV and 0_3^+ state at 12.05 MeV are well established as having the $\alpha+^{12}$C(0_1^+) and $\alpha+^{12}$C(2_1^+) cluster structures, respectively.[13,14] These structures of the 0_2^+ and 0_3^+ states have been confirmed in the present calculation. We also mention that the ground state is described as having a shell-model configuration within the present framework, the calculated rms value, 2.7 fm, agreeing with the observed rms value
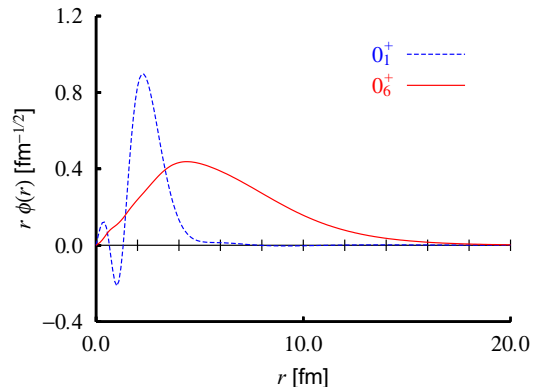
Fig. 1. (Color online) The radial parts of single-α orbits with $L = 0$ belonging to the largest occupation number, for the ground and 0_6^+ states.

(2.71 fm). We find that the 0_6^+ state, calculated to be about 2 MeV above the 4α threshold, has a very large rms radius of about 5 fm and has a rather large occupation probability of 61% of four α particles sitting in a spatially extended single-α $0S$ orbit (see Fig. 1). The wave function has a large $\alpha+^{12}$C amplitude only for ^{12}C*, i.e. the Hoyle state. These results are strong evidence of the 0_6^+ state, which is a new theoretical prediction, for the existence of the 4α condensate state, i.e. the analog to the Hoyle state in ^{12}C. Further experimental information is very much requested to confirm this novel interpretation of this state.

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Holographic Baryons :
Static Properties and Form Factors from Gauge/String Duality [†]

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[Static proeprties of nucleons, Superstring theory]

In this paper, we study properties of baryons by using a holographic dual of QCD on the basis of the D4/D8-brane configuration, where baryons are described by a soliton. Recent progress in string theory makes it possible to compute various physical quantities of strongly coupled QCD at low energy, at large N_c. We first determine the asymptotic behavior of the soliton solution, which allows us to evaluate well-defined currents associated with the $U(N_f)_L \times U(N_f)_R$ chiral symmetry. Using the currents, we compute static quantities of baryons such as charge radii and magnetic moments, and make a quantitative test with experiments. It is emphasized that not only the nucleon but also excited baryons, such as Δ, $N(1440)$, $N(1535)$ etc., can be analyzed systematically in this model. We also investigate the form factors and find that our form factors agree well with the results that are well-established empirically. With the form factors, the effective baryon-baryon-meson cubic coupling constants among their infinite towers in the model can be determined.

We use a model of holographic QCD[1] obtained in superstring theory, and calculate static quantities of the nucleon and excited baryons. In the model, The baryons are described as quantized instantons in five dimensional Yang-Mills-Chern-Simons (YMCS) theory. By defining the chiral currents properly at the spatial infinity in the fifth dimension and by solving the YMCS equations of motion with the instanton profile and Green's functions, we obtain the explicit expression for the chiral currents depending on the baryon state. From the currents we computed various static quantities of proton/neutron, such as charge radii, magnetic moments, axial coupling and axial radius. See the summary table below. The Goldberger-Treiman relation is naturally derived. These quantities can be computed for excited baryons in the same manner, which are our theoretical prediction for the excited baryons. We also calculated the nucleon form factors (and also that for excited baryons). It was shown that the electric and magnetic form factors of the nucleon are roughly consistent with the dipole behavior observed in experiments. Electric as well as magnetic charge radii of the baryons and their cou-

Table 1. Various static observables of nucleons, computed in our model. For a comparison, we quote results of the Skyrmion[2].

	our model	Skyrmion	experiment
$\langle r^2 \rangle_{I=0}^{1/2}$	0.742 fm	0.59 fm	0.806 fm
$\langle r^2 \rangle_{M, I=0}^{1/2}$	0.742 fm	0.92 fm	0.814 fm
$\langle r^2 \rangle_{E,p}$	$(0.742 \text{ fm})^2$	∞	$(0.875 \text{ fm})^2$
$\langle r^2 \rangle_{E,n}$	0	$-\infty$	-0.116 fm^2
$\langle r^2 \rangle_{M,p}$	$(0.742 \text{ fm})^2$	∞	$(0.855 \text{ fm})^2$
$\langle r^2 \rangle_{M,n}$	$(0.742 \text{ fm})^2$	∞	$(0.873 \text{ fm})^2$
$\langle r^2 \rangle_{A}^{1/2}$	0.537 fm	-	0.674 fm
μ_p	2.18	1.87	2.79
μ_n	-1.34	-1.31	-1.91
$\left| \frac{\mu_p}{\mu_n} \right|$	1.63	1.43	1.46
g_A	0.73	0.61	1.27
$g_{\pi NN}$	7.46	8.9	13.2
$g_{\rho NN}$	5.80	-	$4.2 \sim 6.5$

Table 2. Our prediction for excited nucleons.

	n,p	N(1440)	N(1535)
$\langle r^2 \rangle_{E,p}$	$(0.742 \text{ fm})^2$	$(0.742 \text{ fm})^2$	$(0.699 \text{ fm})^2$
$\langle r^2 \rangle_{E,n}$	0	0	0
$\langle r^2 \rangle_{M,p}$	$(0.742 \text{ fm})^2$	$(0.742 \text{ fm})^2$	$(0.699 \text{ fm})^2$
$\langle r^2 \rangle_{M,n}$	$(0.742 \text{ fm})^2$	$(0.742 \text{ fm})^2$	$(0.699 \text{ fm})^2$
$\langle r^2 \rangle_{A}^{1/2}$	0.537 fm	0.537 fm	0.435 fm
μ_p	2.18	2.99	2.18
μ_n	-1.34	-2.15	-1.34
$\left| \frac{\mu_p}{\mu_n} \right|$	1.63	1.39	1.63
g_A	0.734	1.07	0.380
$g_{\pi BB}$	7.46	16.7	6.32
$g_{\rho BB}$	5.80	5.80	4.51

plings to mesons are calculated from the form factors.

As shown in the first table, we have found a good agreement with experiments, for various quantities of baryons. The numerical values presented here as our result should be treated with care, since it was obtained for large value of the 't Hooft coupling and N_c.

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Nondestructive monitoring system of RF fields and beam-phase/intensity for stable operation of RIBF

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We have developed a nondestructive monitoring system of RF fields and beam-phase/intensity in order to obtain stable operation of RI beam factory (RIBF). We have previously reported on a similar system for RILAC region in the last fiscal year[1], but we have extended the system throughout the RIBF in this fiscal year. The layout of the RIBF during a 345 MeV/nucleon uranium acceleration is shown in Fig. 1. In the uranium acceleration, ions are produced by 18GHz-ECRIS, and accelerated by the injection linacs (RFQ and RILAC) and four ring cyclotrons (RRC, fRC, IRC, and SRC). In addition, we have an injection buncher and four re-bunchers as shown in Fig. 1. Two charge strippers are placed downstream of the RRC and the fRC.
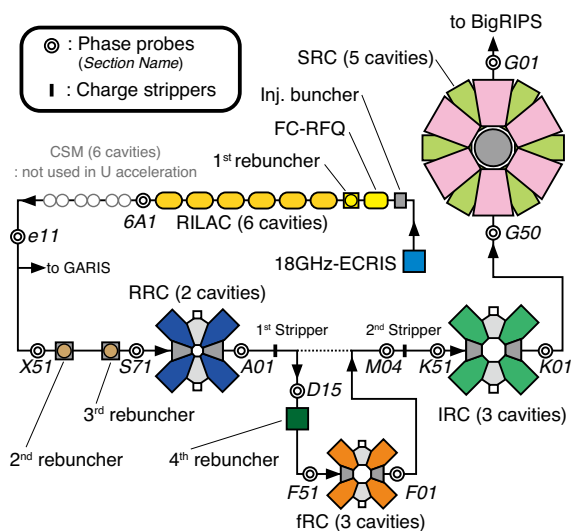
Fig. 1. Layout of RIBF during a 345 MeV/nucleon uranium acceleration.

In such a multi-stage acceleration system, one of the most important factors for stable operation is to maintain the matching of beam-phases between accelerators. However, drifts of beam-phases have frequently been observed, which may be the result of fluctuation of RF-fields, fluctuation of the magnetic field, etc.. Hence, it is important to monitor beam-bunch signals constantly, and we have developed a monitoring system using the commercial RF lock-in amplifier (LIA) model SR844 manufactured by Stanford Research Systems. In addition, the system for monitoring the RF-fields has also been developed to investigate their stability

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and the correlation with beam-phases and intensities. Both beam-bunch signals and the RF-fields monitoring system are divided into 5 sections, which are around RILAC, RRC, fRC, IRC, and SRC. Each section has a monitoring system with basically the same configuration shown in Fig. 2. The beam-bunch and RF-fields signals are analyzed by the LIA (via switching modules in some sections). All the systems are controlled by the developed LabVIEW program. Independently with our monitoring system, the temperatures of air and cooling water are also monitored using DC100 controlled by DARWIN DAQ32 from YOKOGAWA Eelectric Corporation.
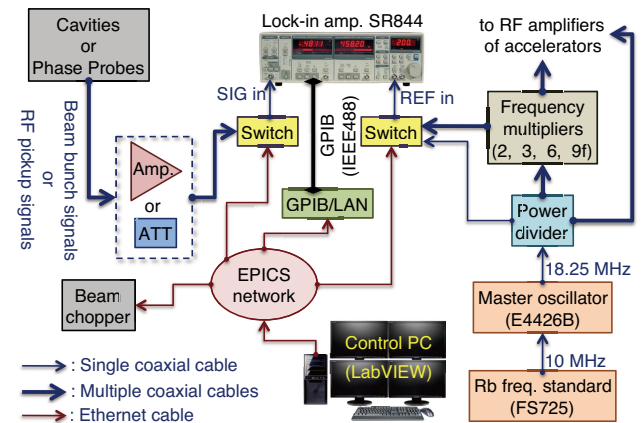
Fig. 2. Block diagram of developed monitoring system.

Our system constantly monitors fluctuations in voltages and phases of a total of 25 RF-cavities and also in beam-bunch signals detected nondestructively by 13 phase probes (PPs, shown as double circles with their section names in Fig. 1.) placed at beam transport lines during 345 MeV/nucleon uranium acceleration. In the other acceleration modes such as 345 MeV/u calcium acceleration using RILAC-RRC-IRC-SRC (skip the fRC), slight changes are made to the configuration of the monitoring system. Using this system, we have started to investigate the stability of our accelerator complex and relations between fluctuations of RF-fields of accelerators and observed instabilities of beam-phases and intensities. In this report, two notable examples are presented.

One is the correlation between RF and air temperature. Since it was known that there was some relation between the output fluctuation of the power divider (1f-PD) and the air temperature according to previous research[2], we investigated the relation between

them more precisely by putting a thermometer near the 1f-PD. This 1f-PD has been used for distributing the reference signal from a master oscillator to each low level module of all RIBF accelerators. Fig. 3-a shows the RF fluctuations observed on November 17, 2008, where fRC3f-PD is the power divider with frequency tripler for fRC main RF, fRC-W and E are the acceleration RF of two main cavities of fRC, and Air-temp. is the air temperature near the 1f-PD. The phase shifts by manual tunings are indicated by arrows. It is found that an air temperature fluctuation
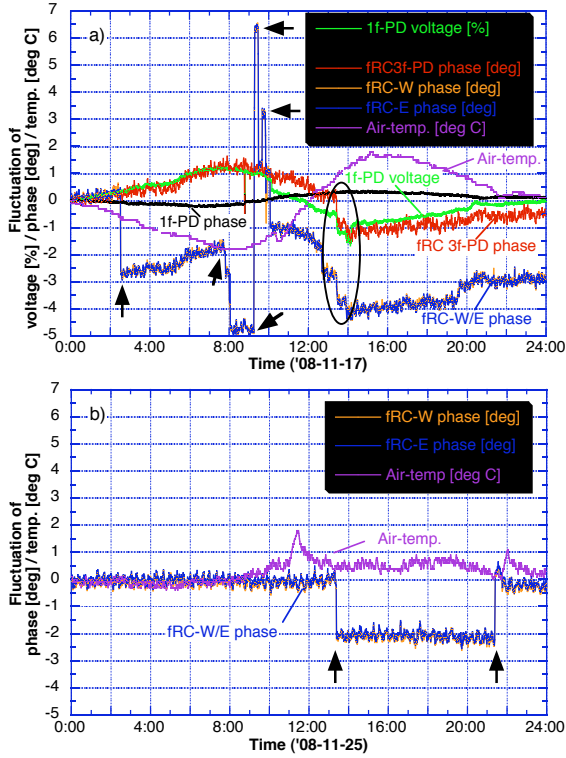
Fig. 3. RF fluctuations of power dividers and fRC. Arrows indicate the phase shifts due to manual tunings.

around 1f-PD of 19.7±2 °C caused phase and voltage fluctuations of 1f-PD and fRC3f-PD, and finally caused phase fluctuations of fRC-W and E of ±3° (excluding the phase shifts by manual tunings). The phase shifts of fRC-W and E caused by the sudden voltage reduction of 1f-PD were also observed independently of the air temperature fluctuation as indicated by the closed circle in Fig. 3-a. The phase stabilities of fRC-W and E were improved as shown in Fig. 3-b after installing the directional couplers instead of the 1f-PD, and after starting air conditioning using a heat pump system.

The other example is the correlation between RF/beam-intensity and cooling water temperature. The periodic fluctuation of extraction intensity of RRC detected by PP-A01 was observed on December 9, 2008. Since the incident intensity of RRC detected by PP-S71 was relatively stable we investigated the RF of the RRC, and it was found that there was a

correlation between them as shown in Fig. 4-a. Additionally, we investigated the cause of fluctuation of RRC-RF, and it was found that it had a correlation with the cooling water temperature of RRC-cavities as shown in Fig. 4-b. The cooling water temperature of RRC-RF system is controlled by regulating the temperature of secondary cooling water by automatically controlling the fans and spray pumps of the cooling tower. We stopped this temperature regulation system because the period of the fluctuation of the cooling water temperature was synchronized with the on/off control of the fans and spray pumps. The stability of beam intensity at PP-A01 was significantly improved after stopping the regulation system as shown in Fig. 4-c, while the stability of RRC-RF was little improved. Hence the fluctuation of beam intensity at PP-A01 can be considered to be caused by the fluctuations somewhere else in origin such as the magnetic field of RRC main magnet, which also has a great influence on the beam quality, and uses same secondary cooling water.
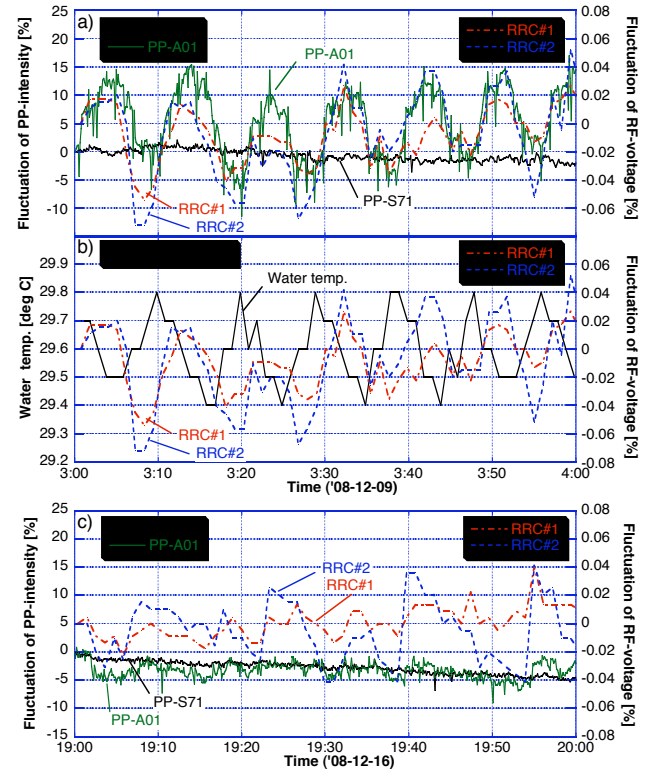
Fig. 4. Stability of extraction beam intensity of RRC.

As our next step, we plan to integrate the temperature monitoring system into our developed monitoring system in order to comprehend the correlations online for more prompt countermeasures.

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A series of asexual mutants and partial deletion of the Y-chromosome by heavy ion beam in *Silene latifolia*

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Sexual dimorphism is controlled by genes on the differential arms of the Y chromosome in *Silene latifolia*. They are divided into four functional regions: (1) a region causing suppression of gynoecium development, often called the gynoecium suppressing functional (GSF) region; (2) a region causing stamen development, also called the stamen promoting functional (SPF) region; (3) a region containing the gene necessary for late anther development, known as the male fertility functional (MFF) region; and (4) a recombining pseudoautosomal region. We have isolated a new series of Y-chromosome deletion mutants, expressed as asexual flowers.

Seeds and anthers were irradiated with a 135 MeV/u carbon-ion beam within a dose range of 20 - 200 Gy. The irradiated seeds were sown in pots, and after one month, viable plants were counted. The survival rates of the seeds irradiated at up to 75 Gy ranged from 100% to 85%. The survival rates of seeds irradiated at more than 75 Gy decreased as the irradiation dose increased. Irradiated pollen was used to fertilize female plants of the same inbred K line. After one month, seeds were collected and sown in pots. The germination rate of seeds generated from pollen irradiated at a dose of 20 Gy was more than 50%, but fell to 3% with a dose of 60 Gy.

Eleven asexual mutants, F01a, I02, G04, G01, G02, I01, G06a, I03h, F02a, G05 and G03, were obtained from the plants derived from irradiated pollen and compared with K034, our previously reported asexual mutant with two types of flowers, asexual and female-like flower.[1] Flowers of *S. latifolia* have 10 stamens and a suppressed gynoecium as an undifferentiated rod (Fig. 1a). Asexual flowers of the eleven asexual mutants had rudimentary or various
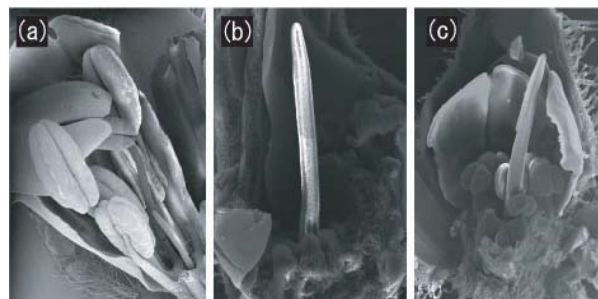
Fig. 1. SEM observations of male flowers of *S.latifolia*. (a) wt male, (b) G06a and (c) F02a.

developing stamens and a suppressed gynoecium (Fig. 1b and c). The number of stamens were always 10 and the two-flower type such as in K034 did not appear among them.

To determine whether the eleven asexual mutants have a Y chromosome, PCR analysis was performed using Y-specific sequence-tagged site (STS) markers (MK17, *SlssY*, Bgl10, *DD44Y*, Bgl16, MS4, ScD05, *SlAP3Y*, ScQ14, MS7 and MS2). K034, which has two flower phenotypes, possessed the Y chromosome carrying two deletions (MS4, Bgl10, *DD44Y*, Bgl16 and ScQ14) in the gynoecium-suppressing and stamen-promoting functional regions (Y^d). Five mutants, F01a, I02, G04, G01 and G02, possessed a Y chromosome carrying a deletion of GSF in common. Another five mutants, I01, G06a, I03h, F02a and G05, possessed a common deletion of SPF. The last mutant, G03, only possessed a deletion of MFF.
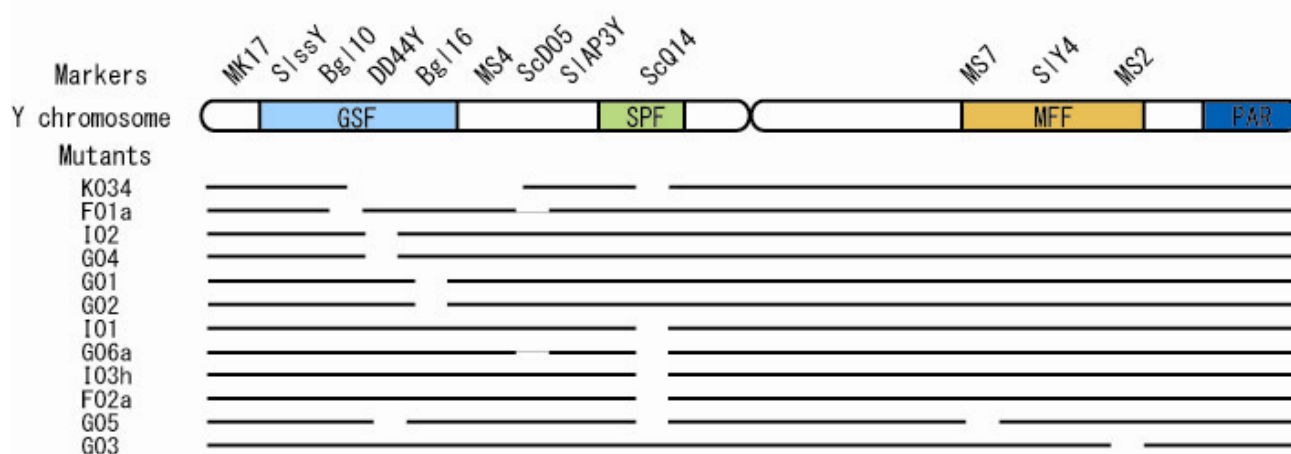
Fig. 2. Schematic representations of the entire Y chromosome of *S. latifolia* and the results of PCR of sequence-tagged site (STS) markers using each genomic DNA isolated from K034 and the series of asexual mutants obtained in this work. Bars for each mutant name represent markers. Blanks indicate the marker was missing.

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C O N T E N T S

2. Nuclear Physics(Theory)

3. Hadron Physics

4. Hadron Physics(Theory)

5. Particle Physics

6. Development of Accelerator Facility

7. Instrumentation

III. RESEARCH ACTIVITIES II (Material Science and Biology)

1. Atomic and Solid State Physics(ions)

2. Atomic and Solid State Physics(muon)

3. Radiochemistry and Nuclear Chemistry

4. Radiation Chemistry and Biology

Ion irradiation in a micro-volume of a cell with a micro beam system for cell irradiation using a tapered

IV. OPERATION RECORDS

1. Operation of RIBF

V. RECORDS OF LABORATORIES, GROUPS, AND TEAMS (Activities and Members)

I. PREFACE

Preface

This volume No. 42 of RIKEN Accelerator Progress Report compiles the yearly research activities conducted in 2008 by the laboratories and the groups of RIKEN Nishina Center for Accelerator-Based Science, or simply RIKEN Nishina Center (RNC) which was inaugurated on April 1, 2006. It also contains progress reports submitted by users of RI Beam Factory (RIBF) and RIKEN-RAL (Rutherford and Appleton Laboratory, UK) Muon Facility (RRMF) which is operated by RNC, and is open to the international community.

The outstanding achievements of this year are selected by the editorial committee, and presented in "Frontispiece" and "Highlights of the Year".

The RIBF project has made some amazing progress, and the RIBF is exhibiting its tremendous potentiality of RI beam production.

In December, with the Zero Degree Spectrometer (ZDS) which was successfully commissioned in November, the first PAC-approved day-1 experiments were performed. Twenty kinds of new very neutron-rich isotopes in the atomic-number range from 29 to 53 as well as more than ten kinds of new neutron-rich short-lived isomers were discovered among fission products of 345MeV/u ^{238}U. This outcome was achieved in only ten days owing to the significant improvement in the intensity and stability of the primary ^{238}U beam, the intensity of which was 0.3 pnA. It was an order of magnitude stronger than in the 2007 experiment but remains yet as weak as a part of 3,300 of its goal. Among those newly discovered isotopes, ^{128}Pd, which is more neutron-rich than $^{125,\ 126}$Pd discovered last year, is remarkable because we have reached neutron-magic nuclide in Pd isotopes for the first time, and it may probably be one of the origin nuclides in the second r-process peak of the solar isotope abundance. It is anticipated that its mass and life-time will be measured precisely using our state of the art experimental installations in the near future.

We have achieved the intensity of 345 MeV/u ^{48}Ca beam of 170 pnA, nearly one fifth of its maximum intensity goal to the wonder and the admiration of the foreign veteran experimentalists. This world's strongest ^{48}Ca beam has led to the discovery of new neutron-hallow nuclides as well as a new very largely deformed nuclide in spite of a very short machine time allocation.

At the same time, 2008 was the year of long, hard struggle for RIBF with a major machine trouble in the helium refrigerators for the SRC and the BigRIPS. These refrigerators were heavily oil-contaminated due to the weak oil elimination power of their oil-driven helium gas compressors. Our cryogenic group persistently negotiated with the manufacturer, and in the end they admitted serious defects in their system. Thus the manufacturer repaired all oil-contaminated parts, and improved oil elimination capacity by adding more oil eliminators, all free of cost. Now the refrigerators are working very stably.

Our GARIS group performed an excellent experiment to firmly establish the evidence of their discovery of the new super heavy element 113 in 2004. They studied decay properties of an isotope ^{266}Bh and its daughter nucleus ^{262}Db produced by the ^{248}Cm (^{23}Na, 5n) reaction. ^{266}Bh was clearly identified from the correlation of the known nuclide ^{262}Db. The obtained α energies and the mean life of ^{266}Bh are consistent with those observed in the ^{278}113. The paper was published in the JPSJ and sent to the chairperson of the joint working team of the IUPAC and IUPAP. We are looking forward to the confirmation of our right to name the new element 113. I personally prefer Japonium Jp. The GARIS group also discovered a new neutron deficient isotope of ^{263}Hs by two different reactions of ^{206}Pb (^{58}Fe, n) and ^{208}Pb (^{56}Fe, n).

In November 4-5, RRMF Advisory Council consisting of 7 members chaired by Prof. A. Taylor, director of ISIS, facility was held in the RIBF building. The followings are the digest of their conclusions and recommendations: the RRMF provides unique instruments which serve a dynamic user community and produce excellent science; condensed matter and molecular science and ultra-slow muon source development should be prioritized; the council recommends extension of the RIKEN-RAL agreement beyond 2010 by at least another 7½ years to 2018.

In November 17-18, RBRC-SRC (RIKEN BNL Research Center Scientific Review Committee) consisting of 6 members chaired by Prof. W. Busza, MIT was held at BNL. The followings are the digest of their conclusions and recommendations: the physics issues addressed by the RBRC are among the most important in sub-nuclear physics, the results obtained to date are highly significant and of long term value; a major strength of the RBRC research program is its focus on one broad topic, QCD; its experimental program and theory program including the lattice computation program are all aimed at understanding the structure and properties of QCD matter; and that there is good reason to believe that prospects are there for the RBRC to continue being a highly successful scientific enterprise with potential for major scientific discoveries.

Nishina Center Advisory Council consisting of 14 members including Prof. A. Taylor, Prof. W. Busza chaired by Prof. S. Gales, director of GANIL will be held on January 15-17. Prof. Gales will report on the review when attending RIKEN Advisory Council (RAC) in April.

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II. RESEARCH ACTIVITIES I

(Nuclear-Particle Physics)

1. Nuclear Physics

γ Spectroscopy beyond the Island of Inversion

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[Nuclear structure, Island of Inversion, neutron-rich nuclei, in-beam γ-ray spectroscopy]

Despite strong theoretical and experimental interest in the rapid nuclear structure changes in and near the Island of Inversion no spectroscopic information is available on the low-lying states of even-even Ne and Mg isotopes beyond neutron number 20 and 24, respectively, and reduced transition probabilities, $B(E2; 0_{gs}^+ \rightarrow 2_1^+)$ values, are only known up to neutron numbers 18 and 22, respectively. This is due to inadequate intensities of beams of these nuclei at presently operating radioactive nuclear beam facilities. This situation has changed with the commissioning of the RIBF, where very intense and high-energy secondary beams can be exploited to study nuclei that have so far been inaccessible.

The first in-beam γ spectroscopic study, demonstrating the potential of the new facility, has been performed in December 2008. A primary ^{48}Ca beam with an average intensity of about 150 particle nA and an energy of 345 MeV/u was impinging on a 20 mm (3.7 g/cm^2) thick rotating Be target located at the F0 focus of the BigRIPS[1] fragment separator. The produced secondary beams were separated using the standard $B\rho$–ΔE–$B\rho$ method employing a 15 mm thick wedge shaped Al degrader at the F1 dispersive focus of the BigRIPS separator. The momentum acceptance was ±3%. The beam particles were identified event-by-event using the standard ΔE–TOF–$B\rho$ method. The time of flight (TOF) was measured between two thin (1 mm and 3 mm) plastic scintillators located at the F3 and F7 achromatic foci (separated by a flight path of about 47 m), the energy-loss was determined with an ion-chamber[2] also located at the F7 achromatic focus and the $B\rho$ was deduced from a position measurement at the dispersive F5 focus of BigRIPS. The figure shows the charge number Z versus the ratio of mass number to charge number A/Q. An excellent charge number and mass number resolution was observed. The location of ^{32}Ne is indicated in the figure.
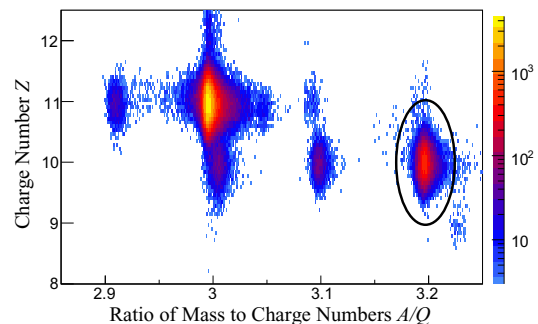
Fig. 1: Shown is the deduced charge number (Z) versus the ratio of mass number to charge number (A/Q) before the secondary target. ^{32}Ne is indicated.

These secondary beams were then transported to the F8 secondary target position where a spot size of about 13×17 mm^2 (FWHM) was realized. To induce inelastic excitations a 14.1 mm (2.54 g/cm^2) thick (natural) carbon target was used. The secondary ^{32}Ne beam with an intensity of about 5 particles/s had an energy of about 225 MeV/u at the center of the secondary target. The emitted de-excitation γ rays were detected by the DALI2 γ spectrometer[3] with a full energy peak efficiency of about 20% and an expected resolution after correcting the large Doppler shift of about 10% for a 1 MeV γ transition. For the particle identification and track reconstruction after the secondary target the newly commissioned Zero Degree Spectrometer (ZDS) was employed, which had an acceptance of about 80% for elastically scattered ^{32}Ne. As before, the ΔE–TOF–$B\rho$ method was applied to unambiguously identify the particles event by event.

After a total measuring time of only 7 hours a γ transition in ^{32}Ne could be clearly identified not only after inelastic excitation, but also after one proton removal from ^{33}Na. The data are currently under analysis.

This constitutes the first observation of a new γ transition in an in-beam experiment at the RIBF and demonstrates the great potential it offers for nuclear structure research in general and γ ray spectroscopy in particular. This measurement campaign will be continued in the fall of 2009, when the full intensity of the ^{48}Ca beam can be utilized.

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Inclusive Coulomb breakup of ^{22}C and ^{31}Ne

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[Halo nuclei, Coulomb breakup]

Soft $E1$ excitation is an unique property of halo nuclei. This property, in turn can be applied to search for a halo state by measuring such an enhancement of E1 reduced transition probability $B(E1)$. As has been done for a number of halo nuclei [1–5], Coulomb breakup is a suitable tool for this purpose.

Present work aims at identifying new halo nuclei in the neutron-drip line region of C and Ne isotopes by the Coulomb breakup. The candidate nuclei we have chosen are ^{22}C and ^{31}Ne, which are heavier than the heaviest known neutron halo nucleus ^{19}C. This work can be a key to understand how the halo nuclei are located along the neutron drip line towards heavier nuclei. ^{22}C is a Borromean nucleus where the two body constituents ^{21}C nor nn system are unbound, with the estimated $2n$ separation energy of only 419(935) keV [6]. On the other hand, ^{31}Ne can be composed of the ^{30}Ne core coupled to the loosely bound p-orbit neutron [7] as the estimated $1n$ separation energy is only 332(1069) keV. The inversion of conventional shell order of $0f_{7/2}$ and $1p_{3/2}$ can be attributed to the deformation and loosely bound nature [8].

The present experiment used the *inclusive* Coulomb breakup where we measured the $1n(2n)$ removal cross sections of ^{31}Ne(^{22}C) on Pb target. Although the best way to study soft E1 excitation is the direct observation of $B(E1)$ energy spectrum by the *exclusive* full kinematical measurement, we have performed an inclusive measurement instead as the latter yield is much larger than the former one. We also measured the same reaction on C target to evaluate the nuclear breakup component in the reaction on the Pb target

The inclusive measurement already provides a significant signal for an enhancement of $E1$ strength at low excitation energies if a nucleus has a neutron halo. This can be easily seen by the fact that the inclusive Coulomb breakup cross section is written as an energy integral of the $B(E1)$ multiplied by the E1 virtual photon number($N_{E1}(E_X)$). Since $N_{E1}(E_X)$ is a steep decreasing function of E_X, the enhancement of $B(E1)$ at low energy is magnified by the photon numbers. Namely, the $B(E1)$ at excitation energies $E_X \sim 1$ MeV alone can contribute to the cross section by an amount of more than 500 mb.

The experiment was performed as one of a series of experiments called "Day-One Campaign" at RI beam factory (RIBF) at RIKEN. The ^{22}C and ^{31}Ne secondary beams were produced through the projectile fragmentation of ^{48}Ca beam at 345 MeV/nucleon on a thick Be target. Typical ^{48}Ca beam intensity was 60 pnA. The secondary beams were separated and focused upon the end point F8 of BigRIPS [9,10], where the secondary targets of lead (3.37 g/cm^2 for ^{31}Ne and 6.74 g/cm^2 for ^{22}C) and carbon(2.54 g/cm^2 for ^{31}Ne and 4.02 g/cm^2 for ^{22}C) were installed. The mean energy of the ^{22}C and ^{31}Ne beams in the Pb target were 230 MeV/u and 234 MeV/u with a typical intensity of 6 cps and 5 cps respectively. Note that these secondary beam intensities are about 10^3–10^4 times more than those previously obtained [11].

For extracting the $1n(2n)$ removal cross sections of ^{31}Ne(^{22}C), the beam particle incident on the target, and the fragment particle following the breakup were identified and counted event by event. For the beam particle, the TOF between F3 and F7 (achromatic foci), ΔE at F7, and position information at F5 (dispersive focus) were combined to determine A and Z of the particle. The fragment particle was analyzed and identified by the Zero-degree spectrometer(ZDS). The configuration of BigRIPS/ZDS can be seen in Fig. 1 of Ref.[10]. The off-line analysis for extracting the Coulomb breakup cross sections for ^{31}Ne and ^{22}C is now in progress.

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Measurement of interaction cross sections for neutron rich Ne Isotopes

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[BigRIPS, reaction cross section, nuclear structure, unstable nuclei]

Measurement of interaction cross sections (σ_I) with fast radioactive isotope beams at relativistic energies allows us to determine nuclear matter radii ($<r_m^2>^{1/2}$) for the unstable nuclei via Glauber model analysis. The formation of a neutron halo in heavier Ne isotopes, where a level inversion of the 1f-2p orbitals is predicted [2], is expected. Evidence of thick neutron skin in neighboring ^{20}N has also attracted our interest [3]. The low production rate, however, has so far prevented measuring their σ_I. The combination of a high intensity primary beam and the next generation fragment separator (BigRIPS) [4] has made such nuclei accessible. Therefore, we have measured σ_I of neutron rich neon isotopes $^{29-32}$Ne as well as those in the region of the island of inversion at 250 MeV/nucleon to determine $<r_m^2>^{1/2}$ of those nuclei.

A schematic drawing of the experimental setup is shown in Fig. 1. The setup is essentially the same as that of our previous experiment at GSI [5]. We employed the transmission method to measure σ_I. A primary beam of 345 MeV/nucleon ^{48}Ca with an intensity of 100 pnA bombarded a Be production target at F0. Produced fragments were pre-separated at the first stage of BigRIPS. The Al wedge-shaped degrader was placed at F1. A 3.6 g/cm^2 thick carbon target was located at F5. The first (F3-F5) and second (F5-F7) halves of the second stage of BigRIPS were used to identify the incident and outgoing secondary beams with the $B\rho$ - ΔE -TOF method, respectively. We used the standard detectors [6] at F3, F5 and F7. We replaced standard plastic scintillators with wider ones (240×100 mm) with 1mm and 3mm thicknesses at F5 and F7, respectively. These scintillation detectors provided both TOF and ΔE information.

An example of a particle identification plot is displayed in Fig. 2. ^{32}Ne intensity was around 5 cps. We accumulated roughly 5×10^4 events of ^{32}Ne, which corresponds to 1 % accuracy in σ_I. The data analysis to determine σ_I is now under way.
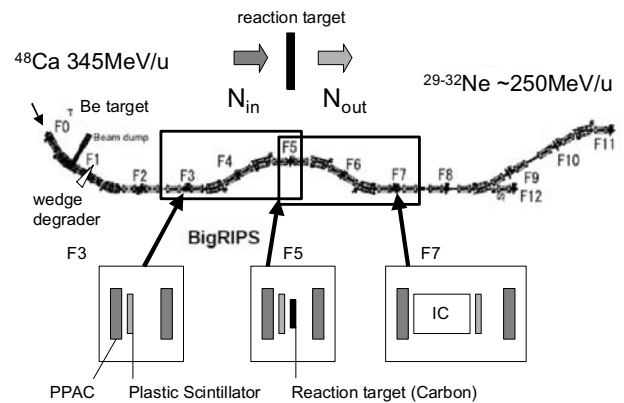
Fig. 1 Experimental setup at BigRIPS. Particle identification of incident and outgoing particles was performed by the $B\rho$-ΔE-TOF method with particle detectors at F3, F5 and F7.
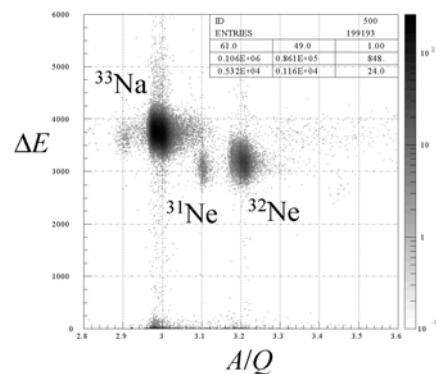
Fig. 2 Typical TOF-ΔE spectrum for the second stage of BigRIPS.

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Angular distributions for low-lying states in the ^{32}Mg(p, p') reaction

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[nuclear structure, in-beam γ-ray spectroscopy]

Proton inelastic scattering on the neutron-rich nucleus ^{32}Mg has been experimentally studied at $E_{\rm lab} = 46.5$ MeV/nucleon in inverse kinematics.[1,2] The energies of excited states in ^{32}Mg were obtained by measuring de-excitation γ rays. Five new states were identified by γ-γ coincidence analysis as shown in Fig. 1. Measured angular distributions of the scattered ^{32}Mg suggest $\Delta L = 2$ and 4 for the excitation to the 885- and 2321-keV state, respectively, as reported in Ref[1,2]. For other excited states, angular distributions were also obtained in the present experiment. Cross sections of excitations to the 5167- and 5204-keV states are found to be 2.9(4) and 2.7(4) mb, which are relatively larger than other states. In the present study, angular distributions were analyzed by DWBA calculations using ECIS97 code[3].

Figure 2 shows measured angular distributions of the excitation to the 5167- and 5204-keV states indicated by dots with statistical error-bars, and calculated curves indicated by solid, dashed, dotted-dash, and dotted curves representing transferred angular momentum (ΔL) of 1, 2, 3, and 4, respectively. DWBA calculations were examined using KD02 optical potential[4] assuming the one-phonon excitation in the harmonic vibrational model. In the calculations, each curve was normalized to the measured cross section, adjusting amplitude parameter β_λ. Comparing with each reduced-χ^2 value for each excited state, candidates of spins were $J = 2$ and 3.

Angular distributions of the 5167- and 5204-keV states are similar to each other. Considering the uncertainty of the γ-ray energy determination, there is a possibility of the same excited state for the 5167- and 5204-keV states. Assuming the one excited state instead of the 5167- and 5204-keV states, the excitation energy could be 5186(28) keV and the cross section is 5.6 mb which is larger than the one of the 2321-keV state (3.7(6) mb). Possible spin assignment for the 5187-keV state may be J of 3, considering the angular distribution and decay scheme. The amplitude
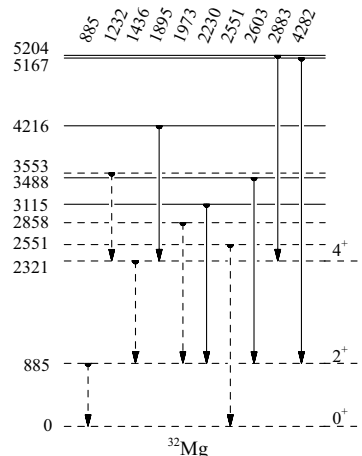
Fig. 1. Reconstructed level scheme of ^{32}Mg deduced from the present studies of the ^{32}Mg+p inelastic scattering. Solid lines and arrows show new levels and transitions, respectively.
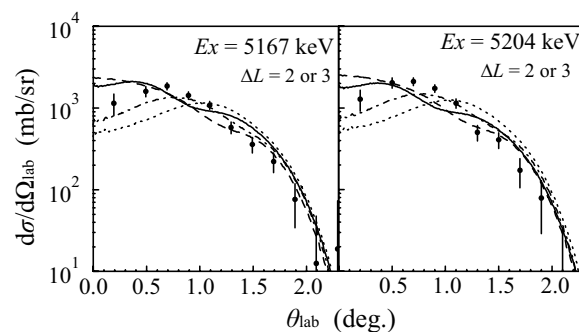
Fig. 2. Angular distributions for the excitation to the higher states around energies of 5 MeV in ^{32}Mg(p, p') reaction.

β_3 of this excitation is found to be 0.171, indicating a possiblility of a 3^- state.

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One-neutron removal reactions of ^{18}C and ^{19}C on a proton target†

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[Nuclear structure, momentum distribution, unstable nuclei]

We have studied the one-neutron removal reactions of ^{18}C at 81 MeV/nucleon and ^{19}C at 68 MeV/nucleon on a liquid hydrogen target to clarify the microscopic structure of these nuclei. Transverse-momentum distributions of the core fragments and partial cross sections were measured using coincidences with γ rays. These were compared to theoretical calculations based on the continuum-discretized coupled-channels (CDCC) method[1] involving shell model spectroscopic factors calculated by the WBP effective interaction.[2]

The experiment was performed at the RI Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo. Secondary beams of ^{18}C and ^{19}C were produced via projectile fragmentation of a primary ^{22}Ne beam at 110 MeV/nucleon on a Be target. The secondary beams were purified by RIPS and were transported to a cell of a cryogenic liquid hydrogen target,[3] which is part of CRYPTA (cryogenic proton and α target system). The average thickness of the liquid hydrogen was 120 mg/cm^2. The incident ion, outgoing core fragment, and de-excitation γ rays were detected in coincidence to obtain the transverse momentum distribution and partial cross section for populating each individual state in the core nucleus. The details of the experimental setup can be found in Ref. 4.

In the one-neutron removal reaction of ^{18}C, we observed two peaks at 0.21 and 0.33 MeV in the energy spectrum of the γ rays emitted from the outgoing core fragment ^{17}C. By comparing the obtained transverse momentum distributions with the CDCC calculations, it was found that the distribution for the 0.21-MeV state is described well by the calculation for neutron removal from the $1s$ orbital in ^{18}C, whereas that for the 0.33-MeV state is consistent with neutron removal from the $0d$ orbital. We thus confirm $J^{\pi} = 1/2^+$ for the 0.21-MeV state and $J^{\pi} = 5/2^+$ for the 0.33-MeV state as deduced in the previous ^{17}C(p, p') experiment.[5]

In the one-neutron removal reaction of ^{19}C, three γ transitions were observed. The measured transverse momentum distribution of ^{18}C in coincidence with the 2.4-MeV γ ray, corresponding to the population of the 4.0-MeV state, is well reproduced by the CDCC calculation by assuming the $0d$-neutron removal. This result leads to the J^{π} assignment of the 4.0-MeV state in ^{18}C. Because $0d_{5/2}$-neutron removal from ^{19}C$(1/2^+)$ populates the $J^{\pi} = 2^+$, 3^+ states of ^{18}C and $0d_{3/2}$-neutron removal produces the $J^{\pi} = 1^+$, 2^+ states, the 4.0-MeV state can be assigned as $J^{\pi} = (1, 2, 3)^+$. The 1^+ assignment is excluded from the following discussion. The cross section for $0d_{3/2}$-neutron removal is expected to be small because the occupation number of the $\nu d_{3/2}$ orbital in the ground state of ^{19}C is expected to be small. In fact, the CDCC calculation with a shell-model spectroscopic factor $C^2 S_{\text{th}} = 0.086$ predicts a cross section of only $\sigma_{\text{th}} = 1$ mb, which is much smaller than the experimental value $\sigma_{\text{exp}} = 35(4)$ mb, indicating the inadequateness of the 1^+ assignment. Hence, we adopt the $J^{\pi} = (2, 3)^+$ assignment for the 4.0-MeV state.

In the present study, we have demonstrated the usefulness of the one-neutron removal reaction on the proton target. It is found that the observed transverse-momentum distributions reflect the orbital angular momentum of the removed neutron, as in the well-studied longitudinal-momentum distributions measured with Be and C targets. We also demonstrated that CDCC analysis is a powerful tool for one-neutron removal from exotic nuclei by a proton target.

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Inelastic proton scattering on the neutron-rich nucleus ^{58}Ti

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[Nuclear structure, ^{58}Ti(p,p'γ), inelastic scattering, unstable nuclei]

The structure of the neutron-rich nucleus ^{58}Ti was investigated via proton inelastic scattering using the technique of in-beam γ-ray spectroscopy. A new region of deformation is suggested in the neutron-rich Cr isotopes around $N = 40$.[1,2] It is interesting to study whether the deformation develops further in nuclei with more neutrons or less protons. We have studied the collectivity of ^{58}Ti ($N = 36$) for the first time.

A ^{58}Ti beam was produced by fragmentation of a 63 MeV/nucleon ^{70}Zn beam with a mean intensity of 150 pnA onto a ^{9}Be target of 95 mg/cm^2 thickness, using the same experimental arrangement described in Ref.[2] The ^{58}Ti nuclei were separated by the RIKEN Projectile-fragment Separator (RIPS).[3] The intensity of ^{58}Ti was 1.5 cps. These nuclei bombarded a liquid hydrogen target[4] of 72 mg/cm^2 thickness. The energy of ^{58}Ti at the middle of the secondary target was 40 MeV/nucleon. The de-excitation γ rays from the inelastically scattered ^{58}Ti nuclei were detected by the NaI(Tl) scintillator array DALI2[5] surrounding the secondary target. The scattered particles were identified using the "TOF mass analyzer for radioactive isotope beam experiments" (TOMBEE)[6] placed downstream of the secondary target.

The Doppler-shift corrected γ-ray energy spectrum measured in coincidence with inelastically scattered ^{58}Ti is shown in Fig. 1 (a). A strong peak at 1046(11) keV, and weak peaks at 1376(18) keV and 1835(27) keV were observed for the first time. The 1046-keV peak was assigned to the $2^+_1 \rightarrow 0^+_{g.s.}$ transition, because the first 2^+ state is most strongly populated by proton inelastic scattering on even-even nuclei.

The energy of the first 2^+ state $[E_x(2^+)]$ in ^{58}Ti is compared with those of other even-even Ti isotopes and Cr isotopes in Fig. 1 (b). The $E_x(2^+)$ value of ^{58}Ti is slightly smaller than that of ^{56}Ti. On the other hand, $E_x(2^+)$ of ^{56}Ti is significantly smaller than that of the sub-shell closed nucleus ^{54}Ti with $N = 32$. This indicates that the increase of the collectivity from ^{56}Ti

to ^{58}Ti is much smaller than that from ^{54}Ti to ^{56}Ti. In contrast, $E_x(2^+)$ of the Cr isotopes decrease continuously from $N = 34$ to $N = 38$, indicating continuous enhancement of the collectivity toward $N = 38$. The larger $E_x(2^+)$ values of Ti isotopes than those of Cr isotopes suggest the weaker collectivity of Ti isotopes. Therefore, the development of the deformation region found in the neutron-rich Cr isotopes does not extend to ^{58}Ti.
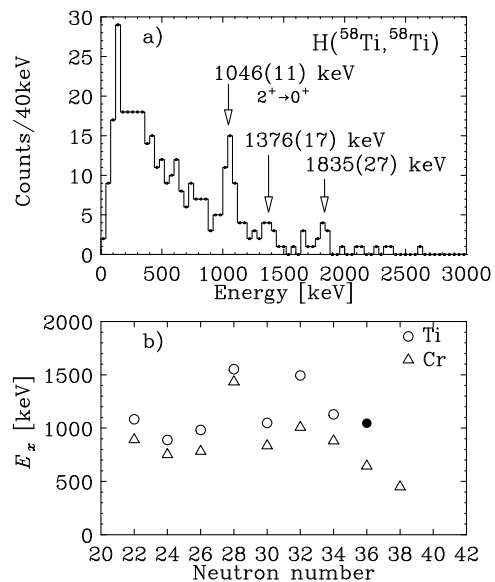
Fig. 1. (a)Doppler-shift corrected γ-ray energy spectrum for the proton inelastic scattering on ^{58}Ti. (b)Plot of the excitation energies of the 2^+ states as a function of the neutron number for Ti isotopes (circles) and Cr isotopes (triangles). The filled circle indicates the result from the present work.

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Inelastic scattering studies of ^{16}C reexamined[†]

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[nuclear structure, unstable nuclei, inelastic scattering]

^{16}C nucleus has been in the forefront of nuclear structure studies in the past years due to several reasons. Its extended neutron distribution was suggested from a reaction cross section measurement[1]. Another interesting phenomenon in the chain of carbon isotopes, opposite deformations between protons and neutrons[2], which inspired several experimental works, were proposed in the mid-nineties by Antisymmetrized Molecular Dynamics (AMD) calculations. In addition, the anomalous long lifetime of the first 2^+ excited state and a corresponding hindered E2 strength was measured by recoil shadow method in RIKEN[3]. Similar small $B(E2)$ value and a strong dominance of neutron over proton excitations were concluded by analyzing the angular distribution of ^{16}C nuclei inelastically scattered on a ^{208}Pb target[4]. This seemed to be confirmed by a proton inelastic scattering measurement in inverse kinematics[5]. This year, the results of two new experiments aimed at redetermining the lifetime of the first 2^+ excited state have become available. RIKEN published a revised data[6] and Lawrence Berkeley National Laboratory has reported a value close to this new result[7]. These studies suggest a shorter lifetime and a corresponding larger $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ between 10-20 e^2fm^4.

In this paper, we present a reanalysis of the inelastic scattering experiments populating the 2^+_1 state using ^{208}Pb[4] and hydrogen targets[5]. Since the Pb and H targets probe the neutron and proton distributions with different sensitivities, both mass and charge, and consequently, the neutron and proton deformation lengths (δ_n and δ_p) can be extracted by comparing the integrated cross sections of the two processes in a simultaneous way.

As a first step, a pair of neutron and proton deformation lengths has been chosen. δ_M^{Pb}, δ_M^{pp}, $\delta_C^{Pb} = \delta_C^{pp} = \delta_p$ are matter and Coulomb deformation lengths for the two probes, respectively.

$$(Z \cdot b_p^{Pb} + N \cdot b_n^{Pb}) \cdot \delta_M^{Pb} = N \cdot b_n^{Pb} \cdot \delta_n + Z \cdot b_p^{Pb} \cdot \delta_p \quad (1)$$

$$(Z \cdot b_p^{pp} + N \cdot b_n^{pp}) \cdot \delta_M^{pp} = N \cdot b_n^{pp} \cdot \delta_n + Z \cdot b_p^{pp} \cdot \delta_p \quad (2)$$

where b_n^{Pb}, b_p^{Pb}, b_n^{pp} and b_p^{pp} are the neutron and proton sensitivity parameters.

$\delta_{M,C}^{Pb}$, $\delta_{M,C}^{pp}$ are the input parameters in the coupled channel code Ecis97 which were used to retrieve calculated cross sections σ_{cal}^{Pb} and σ_{cal}^{pp}. The difference between the calculated and experimental cross sections has been quantified in a χ^2 value so that we ended up with a set of data $(\delta_n, \delta_p, \chi^2)$. This procedure was repeated with varied initial (δ_n, δ_p) parameters and the results are visualized in a contour plot of χ^2 values. From the contour plot, the neutron and proton deformation lengths could easily be determined at δ_n=1.37±0.12 (stat) fm, δ_p=0.90±0.13 (stat) fm. The corresponding proton and neutron transition strengths are:

$$B(E2; 0^+_{gs} \rightarrow 2^+_1)/e^2 = M_p^2 = 15.2 \pm 4.4 \; (stat) \; fm^4 \quad (3)$$

$$M_n^2 = 98 \pm 17 \; (stat) \; fm^4. \quad (4)$$

The total systematic uncertainties due to optical model parameters have been determined at $\Delta\delta_n$=0.095 fm, $\Delta\delta_p$=0.13 fm, ΔM_n^2=14 fm^4, ΔM_p^2=4.4 fm^4. Another source of uncertainty comes from the sensitivity parameters of the probes. The values are not precisely known, and therefore, the dependence of the final data on them has been tested by introducing a 20% change in the $(\frac{b_n}{b_p})^{pp}$ ratio, which alters the $(\frac{b_n}{b_p})^{Pb}$ value consequently. This resulted to the following systematic errors: $\Delta\delta_n$=0.025 fm, $\Delta\delta_p$=0.025 fm, ΔM_n^2=3.6 fm^4, ΔM_p^2=0.8 fm^4.

The presently determined $B(E2)$=15.2 e^2fm^4 value is close to the results coming from the two new lifetime measurements[6,7] of 13.0±1.0 (stat)±3.5 (syst) e^2fm^4 and 20.8±3.7 e^2fm^4 and are consistent with each other taking into account the error bars. However, they are much smaller than 82.3 e^2fm^4 which is expected using a global fit by Raman[8] based on the Grodzins rule[9]. On the other hand, our extracted neutron strength of 98 fm^4 is about 6 times larger than the proton, which shows the dominance of neutron over proton excitations in ^{16}C nucleus.

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Lifetime measurements of excited states in ^{17}C†

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[Nuclear Structure, ^{17}C, excited states, lifetime]

We report on γ-decay lifetime measurements conducted for low-lying excited states of the loosely-bound isotope ^{17}C. The electromagnetic transition strengths were determined for the corresponding deexcitations from the lifetimes observed. The present study aimed to elucidate the low-lying structure of ^{17}C.

The low-lying level scheme of ^{17}C is known to exhibit a couple of unique features. The spin-parity of the ground state was confirmed to be $3/2^+$,[1] which contradicts the naïve shell model expectation that the ground state of an odd nucleus with $N = 11$ should have spin-parity of $5/2^+$. A recent work[2] further revealed two excited states located below the very low neutron emission threshold at 728 keV. These states are almost degenerate with excitation energies of about 220 keV and 330 keV, both deexciting directly to the ground state. In light-mass nuclei, manifestation of such a high degeneracy is exceptional around the ground state. Although spin-parity assignments of $(1/2^+)$ and $5/2^+$ have been made for the first and second excited states, respectively, a comprehensive understanding has not yet been achieved on the underlying structure.

Measurements were performed at the RIPS beamline. The upgraded recoil shadow method (RSM)[5] was applied to the breakup reaction on ^{18}C at 79 AMeV. Details on the RSM are found in Ref.[5]. ^{18}C ions were produced in projectile fragmentation reactions of 110-AMeV ^{22}Ne primary beams with a typical intensity of 320 pnA, impinging on a 1.02-g/cm^2 ^{9}Be production target. The ^{18}C beam had a typical intensity of 2.3×10^4 counts per second with a purity of about 60%, and was directed onto a 370-mg/cm^2 ^{9}Be reaction target set at the final focal plane of RIPS. Positions and incident angles of the secondary beam particles were recorded with two sets of parallel plate avalanche counters (PPACs)[6] placed upstream of the reaction target. Outgoing particles were detected by a plastic scintillator hodoscope,[7] located 3.8 m downstream of the target, facilitating particle identification with the TOF-ΔE-E method. The scattering angle of the particle was determined by combining the hit position on the hodoscope with those on the PPACs for the in-coming particles. An array of 130 NaI(Tl) detectors[8] surrounded the reaction target to detect deexciting γ rays. A 5-cm-thick lead slab was installed close to the target to serve as the γ-ray shield, which is an essential part of the RSM. The slab had an area of 24×24 cm^2 with a 5.4-cm-diameter hole in the center.

Deexcitation γ-rays from the two excited states were clearly observed. The γ-decay mean lifetimes were determined to be 583 ± 21(stat)± 35(syst) ps for the first excited state and 18.9 ± 0.6(stat)± 4.7(syst) ps for the second excited state. Based on a comparison with the empirical upper limits for the electromagnetic transition strengths, these decays were determined to be predominantly M1 transitions. The reduced M1 transition probabilities to the ground state were deduced to be $(1.0 \pm 0.1) \times 10^{-2}\,\mu_N^2$ and $(8.2^{+3.2}_{-1.8}) \times 10^{-2}\,\mu_N^2$, respectively, for the first and second excited states.

The obtained results were compared with those of the stable isotone ^{21}Ne. It is known that ^{21}Ne has an anomalous ground state spin-parity of $3/2^+$ due to its large prolate deformation. The comparison showed that the level properties of the $5/2^+$ states are remarkably similar between the two isotones in terms of the excitation energy and the M1 strength to the ground state. The similarity suggests the enhanced collectivity in ^{17}C, since the $3/2^+$ and $5/2^+$ states form a rotational band in ^{21}Ne. On the other hand, as crossing from ^{21}Ne to ^{17}C, the $1/2^+$ state shows a significant lowering of the state by about 2.5 MeV, accompanied by a strong hindrance of the M1 strength. Naïve Nilsson-model considerations prompted a conjecture that the anomalous behavior of the ^{17}C $1/2^+$ state is related to enhancement of a spatially extended s-wave component anticipated for a loosely bound deformed orbital.

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Investigation of the ^{30}S$(p, \gamma)^{31}$Cl reaction via Coulomb dissociation

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$\left[^{208}\text{Pb}(^{31}\text{Cl},p\ ^{30}\text{S})^{208}\text{Pb, nuclear astrophysics, Coulomb dissociation} \right]$

The stellar reaction ^{30}S$(p, \gamma)^{31}$Cl was studied via Coulomb dissociation. This reaction occurs in the rapid proton (rp) capture process of hydrogen burning on the surface of an accreting neutron star.[1] The nucleus ^{30}S is a candidate for the waiting point, which the reaction flow temporary stops at this nuclei, in the rp process.[2] The ^{30}S$(p, \gamma)^{31}$Cl reaction decreases the amount of ^{30}S, and thus speeds the reaction flow of the rp process up. Therefore the strength of this reaction affects the resultant abundance and energy production in the rp process. ^{31}Cl production in the rp process mainly depends on resonant capture via the first excited state in ^{31}Cl at around 0.6 MeV.[3] No direct measurement of the ^{30}S$(p, \gamma)^{31}$Cl reaction has been made so far due to the short lifetime of ^{30}S and the small cross section of the reaction. We overcome this difficulty by applying the Coulomb dissociation reaction,[4] which can extract the cross section of the relevant stellar reaction with relatively low beam intensity. The aim of the present work is to determine the resonant capture reaction rate of ^{30}S$(p, \gamma)^{31}$Cl through the first excited state in ^{31}Cl.

The experiment was performed using a part of the RIBF accelerator complex operated by RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. The secondary beam of ^{31}Cl at 58 MeV/nucleon was produced by the fragmentation of a 115 MeV/nucleon ^{36}Ar beam on a ^{9}Be target. The fragments were selected by the RIPS with the help of an RF-deflector system.[5] The typical ^{31}Cl beam intensity was about 500 cps, which is about 8% of the total secondary beam intensity. The beam of ^{31}Cl bombarded a 104 mg/cm^2 ^{208}Pb target. The reaction products, the istopes of ^{30}S and protons, were measured by detectors located downstream of the target as shown in Fig. 1. The entire system was in vacuum. The emission angles of the products were measured by a position sensitive silicon telescope located 62 cm downstream of the target. The energy of ^{30}S was also measured by the silicon telescope. The telescope con-
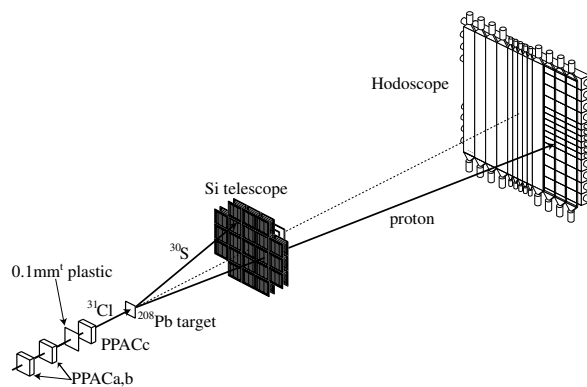
Fig. 1. A schematic view of the experimental setup.

sisted of four layer of detectors arranged in a 5×5 matrix without 4 detectors at the corners of the first and second layer and a 3×3 matrix for third and fourth layer. Each layer was composed of a silicon detector with an effective area of 50×50 cm^2 and thickness of 500, 500, 325, and 500 μm, respectively. ^{30}S was stopped at the fourth layer, and identified using the ΔE and E information. The energy of protons, which penetrated the silicon telescope, was determined with a plastic scintillator hodoscope placed 2.95 m downstream of the target by measuring the time-of-flight (TOF). The hodoscope had an active area of 1×1 m^2, consisting of thirteen 5-mm-thick ΔE- and sixteen 60-mm-thick E-plastic scintillators. The outgoing proton was stopped in the E counters after passing through the ΔE counters. The proton was identified by TOF, ΔE, and E information. The relative energy between ^{30}S and proton was obtained using the measured positions and energies of the products. An array of 160 NaI(Tl) scintillator DALI2[6] was placed around the target to measure de-excitation γ rays from ^{30}S. Analysis of the collected events is in progress.

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Inelastic scattering of proton-rich nucleus ^{23}Al

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[C(^{23}Al,p^{22}Mg)C, C(^{23}Al, ^{23}Alγ)C, Nuclear structure]

The neutron-deficient nucleus ^{23}Al has attracted much attention since its discovery in 1969[1], because ^{23}Al is a candidate for a proton halo system. The 1618 keV γ ray from the $7/2^+$ state in ^{23}Al[2], whose energy is 1.5 MeV higher than the one proton separation energy of ^{23}Al (122 keV[3]) was observed. A candidate for a peak, which may be identical to the $7/2^+$ state, was also observed as a particle decay events of ^{23}Al in the Coulomb dissociation of ^{23}Al.[4] To clarify the structure of this state, the experiment was performed again, with the γ and the particle decays are measured simultaneously.

The experiment was performed using a part of the RIBF accelerator complex operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. The present study was carried out as a by-product of the experiment of the momentum correlation function for ^{23}Al.[5] The secondary beam of ^{23}Al at 72 MeV/nucleon was produced by projectile fragmentation of a 135 MeV/nucleon ^{28}Si beam on a ^{9}Be target. The fragments were selected by RIPS with the help of a RF-deflector sysytem[6] for purifying the secondary beam. The typical intensity and purity of the ^{23}Al beam were 700 cps and 3%, respectively. The beam of ^{23}Al bombarded a 355.4 mg/cm^2 C target. The outgoing ^{23}Al and reaction products, ^{22}Mg and a proton, were detected using a silicon telescope and a plastic scintillator hodoscope located at 62 cm and 2.95 m down stream of the target, respectively. The telescope consisted of five layers of 0.5-mm-thick silicon detectors, and identified ^{23}Al and ^{22}Mg using ΔE-E information. To obtain the scattering angles of the reaction products, silicon detectors which have strip electrodes with 5 mm pitch were used for the first and second layers. Single-element silicon detectors were used for the third, forth and fifth layers. The hodoscope was constructed by three layers of plastic scintillators, which have an active area of 1 × 1 m^2,

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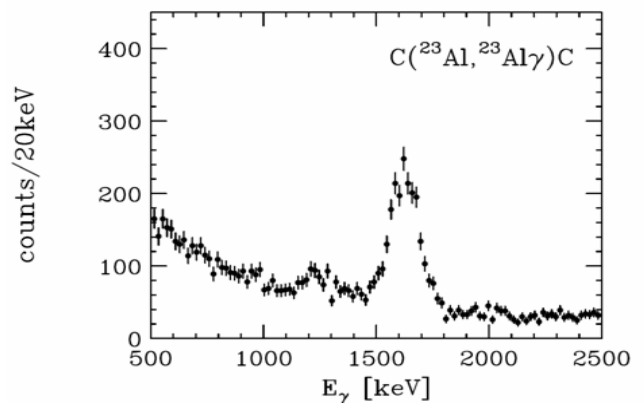
Fig. 1. Doppler-corrected energy spectrum of γ rays measured in coincidence with outgoing ^{23}Al.

consisting of thirteen 5-mm-thick ΔE counters, sixteen 60-mm-thick E1 counters and thirteen 60-mm-thick E2 counters. They detected protons which passed through the silicon telescope. The identification of protons was performed using ΔE-E information obtained from the hodoscope and time-of-flight information between the target and the hodoscope. The γ ray detector array DALI2[7], which was located around the target, was used to measure the de-excitation γ ray from the inelastically scattered ^{23}Al and the reaction product ^{22}Mg.

Figure 1 shows the Doppler-corrected energy spectrum of γ rays. A γ transition from the unbound excited state in ^{23}Al was clearly observed in the present experiment. The energy of the prominent peak may correspond to the γ rays reported by Gade et al.[2] The analysis of the particle decay events is now underway.

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Large proton contribution to the 2$^+$ excitation in ^{20}Mg studied by intermediate energy inelastic scattering

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[NUCLEAR REACTIONS: Pb,C(^{20}Mg,^{20}Mgγ), Coulomb excitation]

Manifestation of nuclear collectivity and shell closure in a wide range of nuclei has recently attracted a great deal of interest, as seen by the recent development of exotic-beam based experiments. The $E2$ reduced transition probability $B(E2)$ and the ratio of proton- to neutron-multipole matrix elements $M_{\rm p}/M_{\rm n}$ for the $0^+_{\rm gs} \to 2^+_1$ transition in even-even nuclei are fundamental quantities that measure the degree of nuclear collectivity. To determine $B(E2)$ and $M_{\rm p}/M_{\rm n}$ for ^{20}Mg, we studied Coulomb excitation of the proton-rich nucleus ^{20}Mg*.

The experiment was carried out using a part of the RIBF accelerator complex operated by RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. A radioactive ^{20}Mg beam separated by RIPS with the help of the RF deflector[1] impinged on a 226 mg/cm^2-thick lead target. The average beam energy in the center of the target was $58A$ MeV. Measurement with a 118 mg/cm^2-thick carbon target was also performed to evaluate the contributions of nuclear excitation. Scattered ^{20}Mg were detected by an array of nine position-sensitive silicon telescopes. Particle identification was performed by the ΔE-E method. De-excitation γ rays from the reaction products were detected by sixty-eight NaI(Tl) scintillators (DALI)[2].

Figure 1 shows the energy spectra of γ rays after correcting for the Doppler shift, measured for the lead and carbon targets when both the beam particle and reaction products are identified as ^{20}Mg. A strong γ line at 1.61(6)MeV is seen in the two spectra. Angular distribution of the scattered ^{20}Mg measured in coincidence with the 1.61 MeV γ rays for the ^{20}Mg+Pb inelastic scattering is consistent with the an-
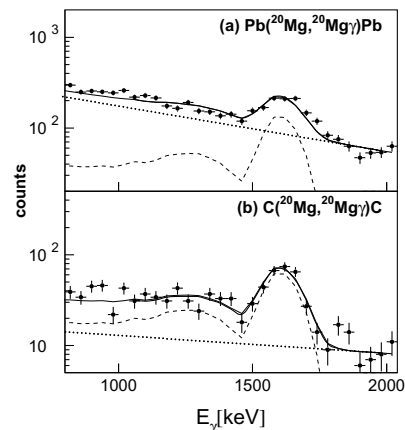
Fig. 1. γ energy spectra after correcting for the Doppler shift in (a) ^{20}Mg+Pb and (b) ^{20}Mg+C inelastic scattering. The solid curve represents the best fit by simulated line shape (dashed curves) and an exponential background (dotted curves).

gular momentum transfer $\ell = 2$, confirming 2^+ assignment to the 1.6 MeV state[3]. To reproduce experimental cross section of the ^{20}Mg+Pb inelastic scattering, $B(E2;0^+ \to 2^+)$ was determined to be 177(32) e^2fm^4, yielding $|M_{\rm p}|$=13.3(12)fm^2.

Assuming the isospin symmetry $M_{\rm p}(M_{\rm n})$ for a transition is equal to $M_{\rm n}(M_{\rm p})$ for the corresponding transition in the mirror partner. The $M_{\rm p}/M_{\rm n}$ value of 2.51(25) for ^{20}Mg was deduced, using the adopted $B(E2)$ value of 28(2) e^2fm^4 for ^{20}O which is considerably larger than the "collective" limit, $N/Z = 1.5$. The extracted $M_{\rm p}/M_{\rm n}$ value can be understood with a simple picture where the ^{16}O core is inert and only four valence protons are responsible for the 2^+ excitation. In this picture, the $M_{\rm p}/M_{\rm n}$ ratio for ^{20}Mg should be equal to $e_{\rm p}/e_{\rm n}$, which results in the ratio 2.6 using standard effective-charge values $e_{\rm p} = 1.3e$ and $e_{\rm n} = 0.5e$. This is in excellent agreement with the present result, and leads to a picture that the shell closure persists in ^{20}Mg.

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Coulomb excitation and proton inelastic scattering of ^{36}Ca

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$$\begin{bmatrix} \text{NUCLEAR REACTIONS: } \text{Pb,}^1\text{H}(^{36}\text{Ca,}^{36}\text{Ca }\gamma), \text{ Pb,}^1\text{H}(^{36}\text{Ca,}^{35}\text{K p}), \text{ Coulomb excitation,} \\ \text{proton inelastic scattering} \end{bmatrix}$$

Coulomb excitation and proton inelastic scattering of the proton-rich nucleus ^{36}Ca were studied to determine $B(E2)$ and M_n/M_p for the $0^+_{gs} \rightarrow 2^+_1$ transition in ^{36}Ca. Recently, the excitation energy of the first 2^+ state in ^{36}Ca was determined using the ^{9}Be(^{37}Ca, ^{36}Caγ) reaction[1]. The excitation energy, 3.015(16)MeV, is 0.44 MeV above the proton separation energy and 0.28 MeV lower than in the mirror nuclei ^{36}S, and the extremely large mirror energy difference was discussed[1]. To obtain further information on the nuclear structure of ^{36}Ca, experimental determination of $B(E2)$ and M_n/M_p is desired.

The experiment was carried out using a part of the RIBF accelerator complex operated by RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. A radioactive ^{36}Ca beam was produced by fragmentation of a $100A$ MeV ^{40}Ca beam in a 1-mm thick beryllium target and separated by RIPS. To improve the purity of ^{36}Ca, an RF deflector was used[2]. Particle identification of the secondary beam was performed event-by-event by measuring time of flight (TOF) and energy loss (ΔE). The TOF was measured using radio-frequency signal of the cyclotron and signal of a 0.1 mm-thick plastic scintillator placed at F3. The ΔE was measured by a 0.1-mm-thick silicon detector. A 226 mg/cm^2-thick lead target was bombarded by the secondary beam. The average beam energy in the center of the target was $58A$ MeV. Measurement with a 52 mg/cm^2-thick liquid hydrogen target was also performed.

Scattering angle of reaction products, ^{36}Ca or ^{35}K+p, were measured by an array of 21 position-sensitive silicon telescopes arranged in a 5×5 matrix, placed 0.62 m downstream of the target. Since ^{36}Ca and ^{35}K particles were stopped in the telescopes, particle identification was performed by the ΔE-E method. The breakup protons punched though the telescopes and were detected by a plastic scintillator hodoscope
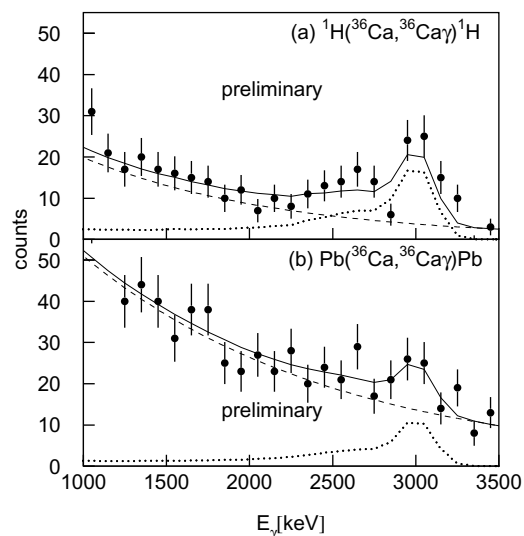
Fig. 1. γ energy spectra after correcting for the Doppler shift in (a) ^{36}Ca+Pb and (b) ^{36}Ca+^{1}H inelastic scattering. The solid curve represents the best fit including simulated line shape (dotted curves) ; an additional exponential background (dashed curves).

consisting of 5 mm-thick ΔE and 60 mm-thick E layers, placed 2.95 m downstream of the target. De-excitation γ rays from the reaction products were detected using 160 NaI(Tl) scintillators (DALI2)[3] surrounding the target.

Figure 1 shows the energy spectra of γ rays measured for the lead and liquid hydrogen targets when both the beam particles and reaction products are identified as ^{36}Ca. The Doppler-shift correction is applied to obtain these spectra. A γ line at 3.0 MeV is seen in the two spectra. Further analysis of the data is in progress.

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Attempt to produce the 3rd chain of $^{278}113$

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$\left[^{278}113, \text{production and decay, gas-filled recoil ion separator} \right]$

In 2003 -2007, we performed an experiment to synthesize an element 113 by a ^{209}Bi + ^{70}Zn reaction using a gas-filled recoil ion separator (GARIS) at RIKEN Nishina-Center. In a total of 241 days of net irradiation time experiment, two decay chains[1,2] were observed and assigned from an isotope $^{278}113$. Both chains were connected to the known nuclei of ^{266}Bh[3] and ^{262}Db[3,4], and ended by a spontaneous fission of ^{262}Db. These latter two decay properties were consistent with reported values[3,4]. The cross section of the ^{209}Bi(^{70}Zn,n)$^{278}113$ reaction was determined to be 31^{+40}_{-20} fb at that time.

In order to increase the number of statistics of the decay property, we continued to produce more decay chains. While the decay chains observed in the previous experiment ended in a spontaneous fission of ^{262}Db , a ^{262}Db would have the possibility to decay by alpha decay. Additionally ^{258}Lr, the daughter nuclei of ^{262}Db, is decaying by alpha decay. If the ^{262}Db were observed in a sequential alpha decay, the decay chain would finally be connected to ^{258}Lr and ^{254}Md which have been well studied. Thus it would be a strong evidence for production of $^{278}113$.

The experiment was carried out from January 7 to March 31, 2008. The experimental conditions were identical to those used in the previous experiment. A ^{70}Zn ion beam of 353 MeV was extracted from RILAC. Targets were prepared by the vacuum evaporation of metallic bismuth onto carbon backing foil of 30 μg/cm^2 thickness. The thickness of the bismuth layer was about 450 μg/cm^2. The beam energy at the halh-depth of targets was estimated to be 349.5 MeV. The reaction products were separated in-flight from the beam by GARIS and guided into a detector box. The detector box consists of five 16-strip silicon detectors. One of the detectors is a position sensitive detector (PSD) which was used as a stop detector. The separator was filled with helium gas at a pressure of 86Pa. The magnetic rigidity of GARIS was set to be 2.09 Tm for evaporation residue.

The net irradiation time was 83 days with a total dose of ^{70}Zn was 2.28×10^{19}. The typical beam intensity on the target was 3.2×10^{12}s^{-1}. The singles counting rate of PSD was about 3 s^{-1} at typical beam intensity. In the present expriment no candidate for $^{278}113$ was not observed. Combining the results of the present and previous experiments, the production cross section of $^{278}113$ was determined to be 22^{+29}_{-14} fb.

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New decay properties of ^{264}Hs, ^{260}Sg, and ^{256}Rf

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$\left[^{264}\text{Hs, } ^{260}\text{Sg, } ^{256}\text{Rf, hassium, seaborgium, rutherfordium, GARIS} \right]$

Decay properties of ^{264}Hs and its α-decay daughter nuclei attract some interest because they are even-even superheavy nuclei. Productions and direct measurements of lifetime of only four atoms of ^{264}Hs were reported previously[1,2]. In this work, the production and decays of ^{264}Hs are investigated using the ^{208}Pb(^{58}Fe,2n) and ^{207}Pb(^{58}Fe,n) reactions.

The ^{58}Fe^{13+} ion beam was extracted from the RIKEN Linear Accelerator, RILAC. The beam energy at the middle of the target in the center of mass frame was set to be 227.2 MeV for ^{208}Pb target and 220.5 MeV for ^{207}Pb. The typical beam intensity was 4.5×10^{12} s^{-1}.

Targets were prepared by vacuum evaporation of lead on carbon backing foil of 30 μg/cm^2 thickness. The target thickness was 500 μg/cm^2 for ^{208}Pb (Enrichment 98.4%) and 430 μg/cm^2 for ^{207}Pb (Enrichment 98.0%). The targets were covered by a 10 μg/cm^2 thick carbon to protect the target from sputtering.

The reaction products were separated in-flight from the beam by a gas-filled recoil ion separator, GARIS, and were guided into a detection system at the focal plane of GARIS. The details about separator and detector is reported elsewhere[3,4].

We observed three correlated events in irradiation of ^{58}Fe on ^{208}Pb, and eight events in irradiation of ^{58}Fe on ^{207}Pb. We assigned these eleven events to be the decays of ^{264}Hs. In the eleven events, ten events were α-decays while one was spontaneous fission decay. Alpha energies of 10.80 ± 0.08 MeV ($I_\alpha = 10\%$), 10.61 ± 0.05 MeV ($I_\alpha = 60\%$) and 10.34 ± 0.04 MeV ($I_\alpha = 30\%$) were observed. The decay time distribution obtained by this work are summarized in Fig. 1. A half-life was deduced to be $0.90^{+0.40}_{-0.20}$ ms. The production cross section was deduced to be $8.5^{+7.7}_{-4.9}$ pb for the ^{208}Pb(^{58}Fe,2n)^{264}Hs reaction and 11^{+5}_{-4} pb for ^{207}Pb(^{58}Fe,n)^{264}Hs.

In the decays of ^{260}Sg, produced as decay daughter of ^{264}Hs and its daughter nuclei ^{256}Rf, we observed two groups. In this report, we describe short-lived nuclei as ^{a}, and long-lived one as ^{b}. ^{260}Sg^a decays by spontaneous fission ($b_{SF} = 60\%$) and α emission ($b_\alpha = 40\%$)

with an energy of 9.78 ± 0.06 MeV and a total half-life of $4.1^{+3.3}_{-1.3}$ ms. ^{256}Rf^a is produced only by α-decay of ^{260}Sg^a, and decays by spontaneous fission ($b_{SF} = 100\%$) with a half-life of 12^{+21}_{-5} ms. These decay properties agree well with the literature values, produced by the ^{208}Pb(^{54}Cr,2n)^{260}Sg and ^{207}Pb(^{54}Cr,n)^{260}Sg or ^{208}Pb(^{50}Ti,2n)^{256}Rf reaction[5].

On the other hand, ^{260}Sg^b decays by α emission with energies of 9.51 ± 0.06 MeV ($I_\alpha = 80\%$) and 8.76 ± 0.08 MeV ($I_\alpha = 20\%$) with a total half-life of 180^{+150}_{-60} ms.

^{256}Rf^b decays by α emission, too. Alpha energies of 8.78 ± 0.04 MeV ($I_\alpha = 80\%$) and 8.47 ± 0.04 MeV ($I_\alpha = 20\%$) were observed with a half-life of $10.4^{+8.4}_{-3.2}$ s. This state is produced only by α-decay of ^{260}Sg^b.

For ^{260}Sg and ^{256}Rf, the decay of such a long-lived state has not been reported. This experiment showed that ^{260}Sg and ^{256}Rf have long-lived state, which is created only by α-decay of ^{264}Hs. These are the first observations of isomerism in ^{260}Sg and ^{256}Rf.

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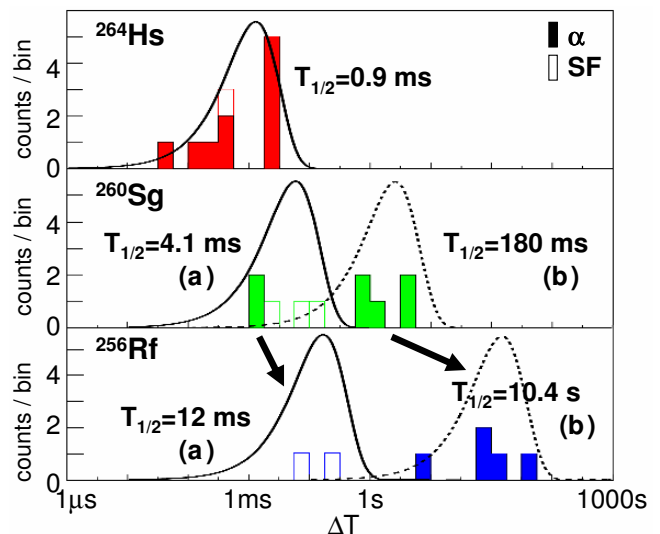
Fig. 1. Decay time distribution in logarithmic scale.

Precision measurement of the hyperfine constant of ^{11}Be

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[hyperfine anomaly, neutron halo, laser spectroscopy]

The magnetic hyperfine structure (hfs) constant of the ground state ^{11}Be$^+$ ion has been measured at the prototype facility of SLOWRI at RIKEN. Energetic ^{11}Be ions produced at the projectile fragment separator RIPS were decelerated and cooled by an RF-carpet ion guide[1] and trapped in a linear RF trap. The stored ^{11}Be$^+$ ions were further cooled by laser irradiation to < 10 mK and double resonance spectroscopy was performed to directly measure the magnetic hyperfine constant a.

The magnetic hfs constant of the s-state is a probe of the magnetization distribution of a nucleus which manifests itself under a local, *inhomogeneous* magnetic field due to a valence s-electron, while the nuclear magnetic moment is an integrated magnetization measured with a *homogeneous* external field. A comparison of the ratio of the hfs constant a to the nuclear g-factor g among isotopes yields the Bohr-Weisskopf effect[2], which should sensitively reflect the structure of the single neutron halo[3]. In the naive picture shown in Fig. 1, the charge radius of ^{11}Be is representative of the core size while the magnetization radius is representative of the radius of the extended halo neutron since the nuclear magnetization is mainly carried by the halo neutron. Combined with our isotope-shift measurements[4], we can clearly discern whether the valence neutron is really distributed with a large radius.

Figure 2 shows the fluorescence intensity for ^{11}Be$^+$ plotted as a function of the microwave frequency. A 313 nm laser radiation was used for the cooling and optical pumping of ions. If a resonant microwave radiation induces the hyperfine transition, the fluorescence intensity changes. From the spectrum the resonance frequency was determined to be 2667.434(10) MHz. We measured two transitions ($|F, m_F\rangle = |0, 0\rangle \leftrightarrow |1, +1\rangle$ and $|0, 0\rangle \leftrightarrow |1, -1\rangle$) at two different magnetic
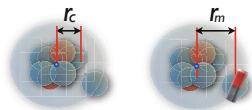
Fig. 2. Microwave resonance spectrum of ^{11}Be$^+$

fields, from which the magnetic hyperfine constant was determined to be $a = -2677.308(2)$ MHz and the nuclear spin was confirmed to be $I = 1/2$.

The differential hyperfine anomaly $^9\Delta^A$ which corresponds with the difference of the Bohr-Weisskopf effect with respect to the stable isotope ^{9}Be is described as

$$^9\Delta^A \equiv \frac{a_9/g_9}{a_A/g_A} - 1 \approx \epsilon_{\mathrm{BW}}(^9\mathrm{Be}) - \epsilon_{\mathrm{BW}}(^A\mathrm{Be}). \quad (1)$$

Fujita *et al.*[5] predicted $^9\Delta^A = 468$ ppm and 950 ppm, while Parfenova and Leclercq-Willaim[6] calculated it to be 320 ppm and 221 ppm using various models. Though the theoretical values diverge depending on the nuclear models used, they all showed a very large anomaly as compared with $^9\Delta^7$ and concluded that the anomaly is correlated with the large neutron spacial distribution. Experimentally, we preliminary evaluated $^9\Delta^A = 220\pm480$ ppm using the inprecise literature value of the nuclear magnetic moment $\mu_I(^{11}\mathrm{Be})=(-)1.6816(8)$ μ_N[7]. In the near future we will measure the Zeeman splittings of the hyperfine structure at a high magnetic field with a combined trap where we can determine the nuclear magnetic moments as well as the hyperfine constants with much higher accuracies as we have demonstrated[8] for ^{9}Be$^+$.

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Fig. 1. Sketch of the charge (r_c) and magnetization (r_m) radii of neutron halo nucleus ^{11}Be.

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Precision hyperfine structure spectroscopy of laser-cooled radioactive ^{7}Be$^+$-ions produced by projectile fragmentation

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[hyperfine constant, magnetic moment, ^{7}Be, laser cooling]

We performed laser cooling and precision hfs spectroscopy of radioactive ions from projectile fragmentation, for the first time, at prototype SLOWRI. The first nucleus measured was ^{7}Be which is a unique nucleus whose nuclear moments elude determination by the $\beta\gamma$-NMR method, since it emits no β-rays and emits γ-rays isotropically. Optical spectroscopy is therefore the only way to measure the nuclear moments.

^{7}Be ions produced at 1 GeV by projectile fragmentation were decelerated and cooled in an RF-carpet ion guide[1,2] and trapped in an RF ion trap[3]. They were further cooled by laser radiation to μeV and laser-microwave double-resonance spectroscopy[5] was performed (Fig. 1)[4]. A magnetic hfs constant of $A = -742.77228(43)$ MHz and a nuclear spin of $I = 3/2$ were determined from the microwave resonance frequencies with σ^+ and σ^- radiations each at two low magnetic fields of 0.61 and 0.71 mT. The nuclear magnetic moment of ^{7}Be was deduced from A to

Table 1. Nuclear magnetic moment of ^{7}Be [μ_N]

Present experimental value	$-1.39928(2)$
Cohen-Kurath (8-16)POT[8]	-1.3787
Ab-initio non-core shell model[9]	-1.138
Variational quantum Monte Carlo[10]	$-1.110(2)$

be $\mu_I(^7\text{Be}) = -1.39928(2)\mu_N$ where the small differential hyperfine anomaly ($^7\Delta^9 < 10^{-5}$ ^{7}) was neglected while the uncertainty of $\mu_I(^7\text{Be})$ was evaluated from a theoretically derived $^7\Delta^9$. Spin expectation values $\langle\Sigma\sigma_z\rangle = 0.94044(3)$ and $\langle\Sigma l_z\rangle = 1.02978(1)$ were also deduced together with the magnetic moment of ^{7}Li[6].

The magnetic moment was compared with theoretical calculations (Table 1). A simple shell model calculation with OXBASH using the Cohen-Kurath[8] interaction shows good agreement, with a 1.5% discrepancy, while the *ab-initio* shell model calculation[9] by Navrátil *et al.*, and the variational quantum Monte Carlo calculations by Pudlinear *et al.*[10] showed large discrepancies of about 20%. These modern calculations achieved good agreement for the magnetic moments of $T = 0$ isoscalar nuclei, such as ^{10}B, but not for $T = 1/2$ isovector nuclei. This is considered to be due to two-body charge and current contributions, which are not included in the calculations; they largely cancel in the isoscalar nuclei, while they are noticeable in the isovector nuclei[11].

We have shown that high precision laser-microwave spectroscopy can be performed for radioactive ions produced at 1 GeV by projectile fragmentation. This guaranties that many new experiments on unexplored isotopes will be conducted using the same setup.
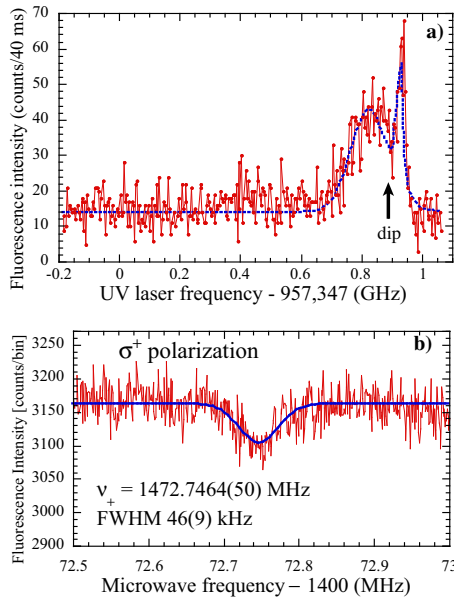
Fig. 1. (a) Laser cooling spectrum of ^{7}Be$^+$ ions and (b) microwave resonance detected by fluorescence intensity in the case of σ^+ radiation.

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Half life measurement of ^{46}Cr

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[β decay, unstable nuclei]

For the rapid proton capture process (rp-process) in X-ray bursts and the core-collapse stage of supernovae, proton-rich pf-shell nuclei far from stability play important roles[1]. Studies of the β and electron capture decays of these proton-rich pf-shell nuclei are of great astrophysical interest. These decays involved in the charged-current processes are predominated by the Fermi and Gamow-Teller (GT) transitions. Information on GT transitions can be derived directly from β-decay measurements. To determine the accurate B(GT), it is important to determine the feeding ratio and half-life of the β-decay accurately.

The purpose of the experiment is to measure the properties of ^{46}Cr, namely, i) the total half-life of β-decay with an accuracy better than 10 %, ii) the decay branching ratios to the ground state (Fermi transition) and GT states accurately.

The experiment to measure the half life of β decay of ^{46}Cr was performed using the low-energy RI beam separator (CRIB)[2,3] of the Center for Nuclear Study (CNS), University of Tokyo. The ^{46}Cr particles were produced by the ^{36}Ar + ^{12}C fusion reaction. A natural C foil of 0.56 mg/cm^2 was installed as the primary target. The ^{36}Ar primary beam was accelerated to 3.6 MeV/nucleon by the AVF cyclotron, and degraded to 3.0 MeV/nucleon by a 2.2-μm-thick Havar foil placed in front of the primary target to maximize production of ^{46}Cr at lower energy. To separate ^{46}Cr from the contaminants produced in the fusion reaction, the Wien filter (WF) was used at a high voltage of ±85 kV. A microchannel plate (MCP) was placed at the final focal plane (F3) to monitor the beam position. We used a 0.7-μm-thick alminized Mylar covered by CsI for the window of the MCP. An ionization chamber (IC) was placed behind the MCP as a ΔE detector. A double sided Si strip detector (DSSD) of 500-μm thickness was set in the IC as an E and a β-ray detector. A Si detector of 1.5-mm thickness was placed behind the DSSD for a β-ray detector. To measure β-delayed γ rays involved β decay, 3 clover and 1 coaxial Ge detectors were set around the IC. The beam was pulsed to measure the half life of the β decay of ^{46}Cr. The durations of the beam-on and beam-off periods were 500 and 700 ms, respectively. Non-stop TDC (NSTDC) was used to measure half lives of fusion products.

Figure 1 shows a particle identification obtained
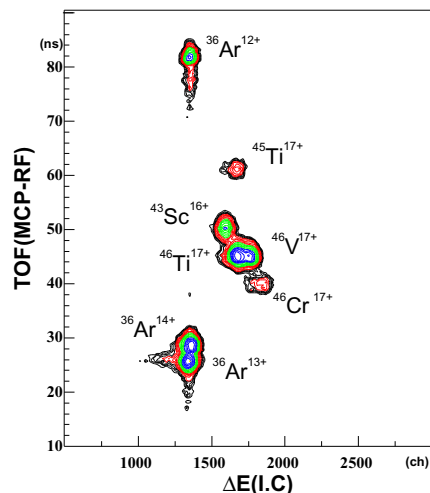
Fig. 1. RF-ΔE spectrum obtained by the IC and MCP placed at F3.

from the ΔE and the time-of-flight (TOF) from the MCP and the RF signals. ^{46}Cr was clearly separated from other products. In this experiment, the purity and the intensity of ^{46}Cr were 2 % and 10 particle per second (pps) with the primary beam of 80 particle nA.

Figure 2 shows a decay spectrum of NSTDC between duration of beam off. This spectrum was made by only setting gates on more than 200 keV of DSSD, which is mainly dominated by the ^{46}V decay. Further analysis is in progress to get a clean spectrum.
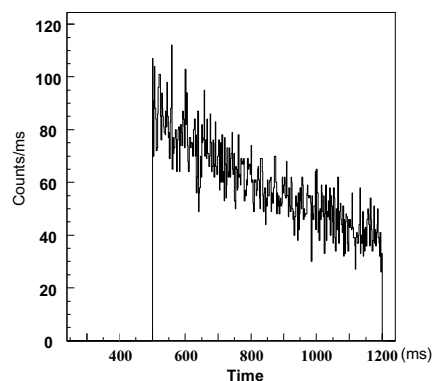
Fig. 2. Decay spectrum.

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^{30}S Beam Development with CRIB

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[Unstable nuclei, astrophysics]

The ^{30}S(α,p) reaction is a significant link in the rapid proton capture process in X-ray bursts on accreting neutron stars[1], but there are no experimental data to date. In order to perform a successful measurement of the ^{4}He(^{30}S,p) cross section at X-ray burst energies, Hauser-Feshbach calculations indicate we require a ^{30}S beam of $\sim 10^5$ particles per second (pps) at 32 MeV.

We conducted beam development experiments in 2006 and 2008 using the low-energy Center for Nuclear Study (CNS) radioactive ion beam (CRIB) separator facility[2,3] of the University of Tokyo and located at the Nishina Center of RIKEN. We produce ^{30}S via the ^{3}He(^{28}Si,^{30}S)n reaction, by bombarding a cryogenic gas target[4,5] of ^{3}He at 90 K with beams of ^{28}Si. We tested two primary beams: ^{28}Si^{9+} (6.9 MeV/u and 130 pnA); ^{28}Si^{10+} (7.54 MeV/u and 10 pnA); both beams were extracted from the CNS HyperECR ion source and accelerated by the AVF cyclotron. We tested three production target gas pressures (200, 300, 400 Torr), finding ^{30}S yield was maximized at the highest ^{3}He gas pressure.

RI Species	E_{beam} (MeV)	Purity (%)	Intensity (pps @ 10 pnA)
^{30}S^{16+}	30	30	500
^{30}S^{14+}	32	0.8	1.2×10^4

Table 1. Selected results for ^{30}S beams, using ^{3}He at 400 Torr and the primary beam ^{28}Si^{10+} at 7.54 MeV/u.

The ^{30}S beam profile is monitored with delay-line PPACs and energy is measured with a Si detector at the target focus. Results are presented in Table 1 and Fig. 1. For both ^{30}S experiments, the Wien filter potential was ± 60 kV, but it has achieved up to ± 100 kV, allowing higher ^{30}S purity in future, which we like to be $\geq 10\%$ due to the 10^6 Hz PPAC counting limit. We attempted to increase the purity of ^{30}S^{14+} using a 1.5 μm aluminized mylar degrader at the momentum dispersive focal plane, but the intensity on target decreased by 80% because the CRIB optics were not improperly retuned due to time constraints. It should be possible to accelerate ^{28}Si^{9+} to 7.4 MeV/u at 130 pnA, increasing the ^{30}S^{14+} intensity by a factor of 13 to
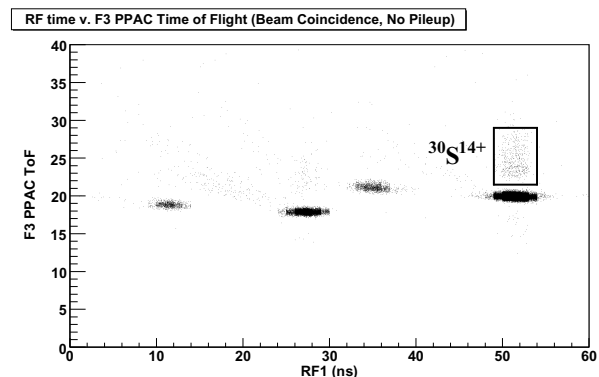
Fig. 1. RF-ToF spectrum using delay-line PPACs in the scattering chamber. ^{30}S^{14+} is clearly separated.

above the requisite 10^5 pps. We also tested, but could not fully separate ^{30}S^{15+} from the primary component ^{28}Si^{14+} due to similar magnetic rigidity.

We measured the charge-state distribution of ^{28}Si beam ions in carbon (550 μg/cm^2) compared to Havar foil (2.2 μm) (Table 2). For a ^{28}Si beam of 3.4 MeV/u ($\sim E_{beam}$ of ^{30}S), it was found that transmission of highly charged states of ^{28}Si is improved through carbon foil compared to Havar foil with a ratio consistent with predictions of LISE++. It may be possible to preferentially populate higher charge states of ^{30}S by use of a carbon stripper foil.

Target	Species	Normalized pps @ 10 enA
Havar	^{28}Si^{12+}	1.075×10^8
Havar	^{28}Si^{13+}	6.013×10^7
Havar	^{28}Si^{14+}	3.901×10^6
Carbon	^{28}Si^{12+}	1.758×10^8
Carbon	^{28}Si^{13+}	1.300×10^8
Carbon	^{28}Si^{14+}	4.365×10^7

Table 2. Intensity of selected charge states of ^{28}Si after passing through Havar foil or carbon foil.

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Study of astrophysically important states in ^{26}Si via the p(^{25}Al,p)^{25}Al elastic scattering

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Galactic ^{26}Al in its ground state is produced by the proton capture on ^{25}Mg. In nova explosions, the proton capture of ^{25}Al competes with its β decay to supply the ^{25}Mg and therefore bypasses the production of ^{26g}Al, since the capture product ^{26}Si decays quickly to ^{26m}Al instead of its ground state. At even higher temperatures, such as in supernova explosions, ^{26m}Al can be excited to the higher excited states by thermal excitation and then quickly de-excite to the ground state, thereby enhancing the production of ^{26g}Al[1]. The energy levels in ^{26}Si in the Gamow window corresponding to these temperatures therefore need to be well understood in order to determine the ^{25}Al$(p,\gamma)^{26}$Si reaction rate, and thus the production rate of ^{26}Al in these explosive environments[4–7].

A thick target method[2,3] was used to scan the center-of-mass energy from 0 to 3.38 MeV with the secondary beam of 3.52 MeV/nucleon ^{25}Al impinging on the 6.58 mg/cm^2 CH$_2$ target, corresponding to a range of excited states from 5.515 MeV (^{25}Al$+p$ threshold) to about 8.9 MeV. The ^{25}Al beam was produced by the reaction ^{2}H(^{24}Mg,n)^{25}Al, with the purity of about 50% and intensity of about 5×10^5 pps on target. The particle identification (PID) for the secondary beam was provided by two PPACs (Parallel Plate Avalanche Chamber) while PID for the scattered protons was provided by ΔE-E telescopes as well as the TOF (time-of-flight) method.

The energy loss of the scattered proton traveling through the remaining part of the target must be taken into account. The total yields of background protons of different energies from a carbon target are normalized by the ratio of target thickness per energy bin and the ratio of the total number of beam events. Figure 1 shows a final proton spectrum after correcting the energy loss and subtracting the background protons.

For preliminary purpose to find the resonant energies, a Breit-Wiger fit was applied for each single peak in the proton spectrum. Figure 2 shows a sample fit.
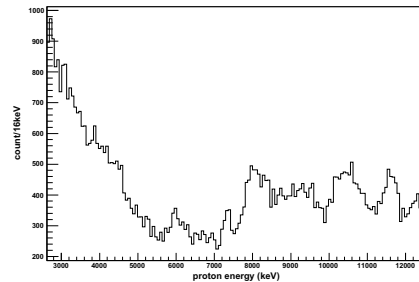
Fig. 1. Proton spectrum at $\theta_{lab}= 0^o$ in the center of mass frame with energy loss corrected and background subtracted.
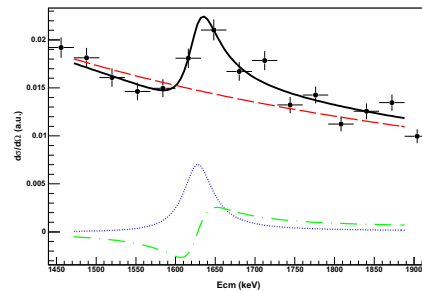
Fig. 2. A Breit-Wigner fit for the peak at E_{cm}=1697keV, corresponding to the excited state E_x=7156keV, J^π=2$^+$,[7] with the dashed line for the Coulomb part, dashed-dotted line for Coulomb-resonance interference and the dotted line for the pure resonant part.

An advanced R-Matrix[8] fit for the excitation function is being performed to extract physical parameters such as energy levels and proton widths. The results will be used as input for calculating the new ^{25}Al$(p,\gamma)^{26}$Si reaction rate. The analysis is still in progress.

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Measurement of the ground-state electric quadrupole moment of ^{33}Al

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[Nuclear structure, magnetic moment, unstable nuclei]

In the work currently being carried out, the ground-state Q moment of ^{33}Al ($I^\pi = 5/2^+$, $T_{1/2} = 41.7(2)$ ms) has been measured by means of the β-ray detected nuclear magnetic resonance (β-NMR) spectroscopy[1] incorporating the technique of fragmentation-induced spin-polarized radioactive isotope beams[2,3].

The experiment was carried out at the GANIL facility. A beam of ^{33}Al was obtained from the fragmentation of ^{36}S projectiles at $E = 77.5A$ MeV on a 224 mg/cm^2-thick ^{9}Be target. In order to have ^{33}Al spin-polarized, fragments emitted at angles $\theta_\text{Lab} = (1 - 3)°$ from the primary beam direction were accepted by the LISE spectrometer: the primary beam was deflected by 2° with respect to the target located at the spectrometer entrance. Also, a range of momenta $p = (1.026 - 1.041)p_\text{b}$ was selected with a slit placed at the momentum-dispersive intermediate focal plane. Here $p_\text{b} = 11.7$ GeV/c is the fragment momentum corresponding to the projectile velocity. Under the above conditions and with a primary ^{36}S^{16+} beam current of $I \sim 2$ $e\mu$A, LISE provided the beam of ^{33}Al with a purity ~ 75 % and an intensity of 1.3 k particles/s. Then, the spin-polarized ^{33}Al were transported to a β-NMR apparatus located at the final focus of LISE, and were implanted in a stopper of α-Al$_2$O$_3$ single crystal of hexagonal structure. A static magnetic field $B_0 \sim 500$ mT was applied to the stopper in order to preserve the spin polarization. The α-Al$_2$O$_3$ crystal was mounted in a stopper chamber so that the c-axis was oriented parallel to the B_0 field. The stopper was kept in a vacuum and cooled to a temperature $T \simeq 80$ K to suppress the spin-lattice relaxation of ^{33}Al during the β decay.

The Q moment was measured based on the β-NMR technique, where resonance is observed through the change in the β-ray up/down ratio R measured with plastic scintillator telescopes located above and below the stopper. By taking a double ratio R/R_0 where R_0 is the value for R measured without an oscillating magnetic field B_1, the resonance frequency is derived from the position of a peak or dip deviating from unity. The obtained NMR spectra are shown in Fig. 1.

The experimental quadrupole coupling constant $|eqQ/h|$ of ^{33}Al can be determined from the peak positions in the spectra, with which the experimental $|Q(^{33}\text{Al})|$ is deduced from the relation $|Q(^{33}\text{Al})| = |Q(^{27}\text{Al}) \cdot eqQ/h(^{33}\text{Al})/eqQ/h(^{27}\text{Al})|$, where $Q(^{27}\text{Al})$ and $eqQ/h(^{27}\text{Al})$ denote the Q moment of ^{27}Al and the quadrupole coupling constant of ^{27}Al in α-Al$_2$O$_3$, respectively. Based on the least-χ^2 fitting analysis adopted to the determination of $|Q(^{31}\text{Al})|$[4], a preliminary value $|Q(^{33}\text{Al})| = 132(16)$ $e$mb has been determined. The analysis is in progress.
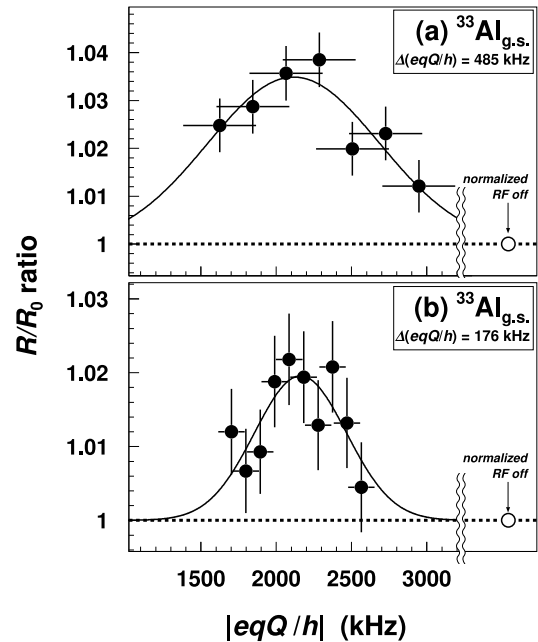
Fig. 1. NQR spectra obtained in an α-Al$_2$O$_3$ single crystal for the ^{33}Al ground state by applying (a) wider and (b) narrower frequency windows of the B_1 field. In the spectra, double ratios R/R_0 are plotted as a function of the quadrupole coupling constant $|eqQ/h|$, where R_0 is the value for β-ray up/down ratio R measured without the B_1 field. The result of the least-χ^2 fitting analysis is shown by solid curves.

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Electric quadrupole moment of proton-rich ^{23}Al

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[nuclear structure, spin-polarized RI beam, electric quadrupole moment, β-NMR/NQR]

Proton-odd nuclei in the sd-shell near the proton-drip line have much smaller proton-separation energies compared with stable nuclei. In particular, for ^{23}Al ($I^\pi = 5/2^{+,1)}$ $T_{1/2} = 470$ms), the separation energy is extremely small as 125(25) keV, and so ^{23}Al is considered to be a candidate of the proton-halo nucleus. Recently, a large reaction cross section, although error was still large, was reported[2,3] and the authors suggested halo-like structure of ^{23}Al. Note that there is at least one candidate of the proton-halo like nucleus whose spin-parity is not $1/2^+$, e.g. ^{8}B[4] in the p shell. In this work, the Q moment of ^{23}Al has been measured by β-ray detected Nuclear Quadrupole Resonance method (β-NQR method) to extract information about nuclear matter density distribution.

The experiment was carried out by utilizing the RIKEN Projectile Fragment Separator (RIPS) at the RI Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo. Nuclear spin-polarized ^{23}Al nuclei were produced by bombardment of ^{24}Mg ions on a 2.5 mm-thick ^{9}Be target. The ^{24}Mg^{12+} ions were accelerated up to 100 MeV/nucleon and the intensity of the primary beam was typically $\sim$800 enA on the target. The production process, ^{24}Mg $+^9$ Be $\to^{23}$ Al+X, is considered as a composite process of the pickup and the projectile fragmentation processes. The fragments which are emitted into the angle from 0.4° to 5.4° relative to the primary beam with the momentum below 1.05 p_0, where $p_0 = 8.76$ GeV/c is the peak in the distribution, were selected by RIPS, and the degree of polarization of ^{23}Al was measured as 1.2% by the β-NMR method. A wedge-shaped degrader (221 mg/cm^2) was used for the energy loss separation, and then the ^{23}Al ions were transported to the β-NQR apparatus and were implanted into a α-Al$_2$O$_3$ plate together with inseparable fragments such as ^{22}Mg and ^{21}Na which became low energy-β-ray emitters. By β-ray energy separation, the purity was achieved to $\sim$74% in β-ray counts and the counting rate was typically $\sim$100 cps. Static magnetic field $B_0 = 0.458$T was applied on the crystal parallel to the polarization axis in order to preserve the polarization and to induce the Zeeman splitting. Electric field gradient $q = V_{zz}$ at

the implantation cite of ^{23}Al in α-Al$_2$O$_3$ interacts with the $Q(^{23}$Al$)$ as a perturbation which is characterized by a quadrupole coupling constant eqQ/h. In β-NQR method, using plastic-scintillation-counter telescopes which are placed above and below the crystal relative to the polarization, the asymmetrical β-ray emission were detected as a up/down counting ratio. Oscillating magnetic field B_1 was applied perpendicular to the B_0. When applied frequencies corresponds to the eqQ-perturbed Zeeman splitting, the polarization was resonantly changed, in other words, the up/down ratio was resonantly changed at the eqQ/h.

Obtained NQR spectrum is shown in Fig. 1. In Fig. 1, the β-ray asymmetry was expressed as the up/down ratio normalized by the up/down ratio without B_1 field as a function of eqQ/h. From the peak position of the resonance and comparison with ^{27}Al of which the Q moment[5] and the quadrupole coupling in α-Al$_2$O$_3$[6] are well studied, the Q moment of the ^{23}Al is determined as $|Q| \sim 170$ $e$mb from the preliminary analysis. Detailed analysis is in progress.

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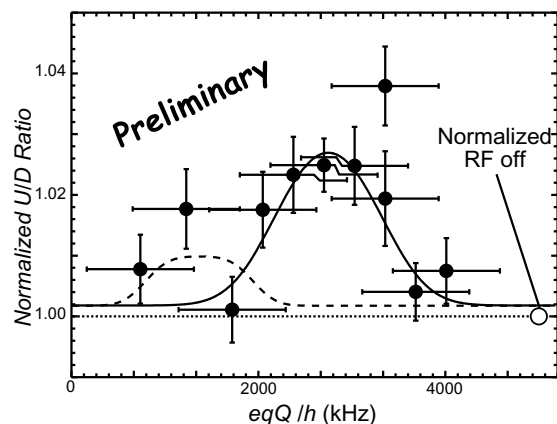
Fig. 1. NQR spectrum of ^{23}Al in α-Al$_2$O$_3$ at room temperature. The solid line shows the result of preliminary analysis based on the least-χ^2 fitting.

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Production of ^{58}Cu through the charge exchange reaction of ^{58}Ni

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[Charge exchange reaction, unstable nuclei]

Nuclei near the double magic nucleus ^{56}Ni are of particular interest in investigating structure and interaction in the pf-shell region[2]. The $N=Z$ odd-odd nucleus ^{58}Cu($I^\pi = 1^+$, $T_{1/2} = 3.2$ s) with one proton and one neutron outside the ^{56}Ni core is the best suited system for the study of proton-neutron interaction in a pf shell nucleus. We then plan to determine the electromagnetic moments of ^{58}Cu by means of the β-NMR technique[1].

Also the short lived β-emitter ^{58}Cu might be an attractive β-NMR probe for material science. For example in a Si device, a Cu impurity causes degradation of its performance because of the fast diffusivity and formation of deep impurity levels in the band gap[3]. β-NMR studies with ^{58}Cu as a microscopic probe should be able to provide unique information on the mechanism of Cu diffusion and the behavior of Cu-dopant complex (ex. Cu-B pair) in Si.

In this report, we present results for the production of ^{58}Cu through a charge exchange reaction of ^{58}Ni, as the first step of establishing a spin polarized ^{58}Cu beam for β-NMR studies. A 95A MeV ^{58}Ni beam was provided by the K540 RIKEN Ring Cyclotron and impinged on a 2-mm thick Be target. The ^{58}Cu nuclei emitted at angles $0.2°-4.5°$ were separated by RIPS. An 85-mg/cm^2 thick curved Al plate was used at F1 as an achromatic degrader.

Particle identification was done with a standard particle detector system at RIPS. The momentum distribution for ^{58}Cu was obtained as shown in Fig. 1 and the width is almost explained by energy spread due to the target thickness. The momentum of the peak for ^{58}Cu is nearly the same as the momentum that corresponds to the primary beam velocity.

The size of the secondary beam was about 15 mm in diameter at the final focus point F3 where the β-NMR equipment is to be installed. Production of ^{58}Cu was also confirmed from the β-ray time spectrum measured at F3 as shown in Fig. 2.
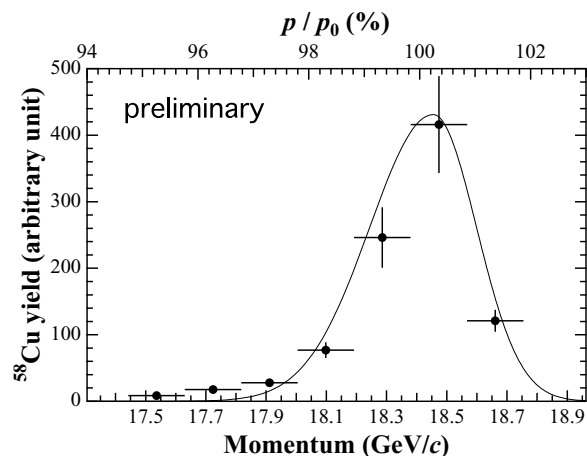
Fig. 1. Momentum distribution of ^{58}Cu produced through the charge exchange reaction of ^{58}Ni with a Be target.
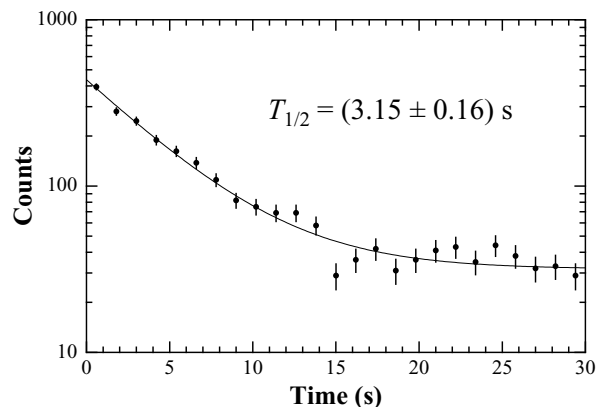
Fig. 2. Typical β-ray time spectrum for ^{58}Cu.

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The first T-violation experiment using polarized ^{8}Li at KEK-TRIAC

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[β decay, spin polarization, symmetry]

The beta-decay rate function W can be expressed as

$$W \propto 1 + A\frac{\vec{J} \cdot \vec{p}}{E} + R\frac{\vec{J} \cdot (\vec{p} \times \vec{\sigma})}{E} \cdots,$$

where $\vec{J}$ denotes spin of the parent nucleus, and E, $\vec{p}$ and $\vec{\sigma}$ indicate energy, momentum and spin of electrons, respectively. A is the beta-decay asymmetry parameter, and R is the coefficient we are interested in. Production of polarized nuclei, measurement of electron momentum, and measurement of electron transverse polarization are required to determine the R coefficient. If a non-zero R is observed, it means that time reversal symmetry is violated.

A physics experiment (RNB08K04) was performed in September 2008 using a polarized ^{8}Li beam at KEK-TRIAC, and R-parameter measurement was performed. The detector setup is shown in Fig. 1. Regarding the Mott polarimeter, a multi-wire drift chamber has been developed as an electron tracking detector.[1] The polarized ^{8}Li is produced using the tilted-foil technique.[2] In the present experiment, polystyrene ($3\,\mu$g/cm^2) foil was used with a tilting angle of 70°. Systematic error of the detector system can be canceled by changing the foil angles every 5 minutes. A special beam stopper was developed at the Van de Graaff accelerator at Osaka University.[3] A large platinum foil (t-20 μm, annealed) was used to catch the diffused beam efficiently. A magnetic field ($>$500 Gauss) was applied using a pair of small permanent magnets in order to minimize the size of the entire stopper. It is known that transversely polarized electrons show up-down asymmetry in Mott scattering. Electron transverse polarization can be determined by obtaining the scattering angular distribution from the observed scattering tracks.

A new trigger system was developed for the September experiment. The previous trigger logic consisted of coincidence signals between scintillators. In the new system, the trigger purity (ratio of real scattered "V-tracks" events to all recorded events) is quite small. To improve the poor V-track efficiency, the hit signals from the drift chamber are included in the trigger logic. Using this new trigger system, the trigger rate can be reduced to 1/20 without losing real events.

We successfully reconstructed the tracks for the Mott scattered electrons. The value of the R-parameter was roughly estimated from the asymmetry

Fig. 1. Detector setup.

of the scattering angular distributions (Fig. 2), yielding $R = 0.30 \pm 0.18$ (statistics only). This value is inconsistent with zero. More precise experiments are required to determine whether time reversal symmetry is violated or not.
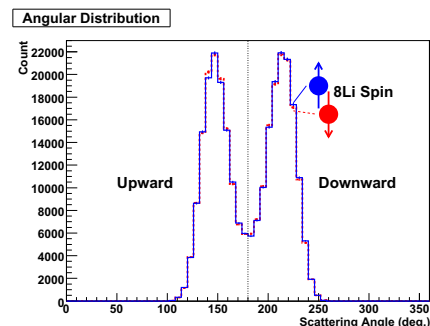
Fig. 2. Obtained angular distribution of Mott scattering.

Our future experiments will be performed at TRIUMF-ISAC. Since the beam intensity and polarization are greatly increased, a better result will surely be obtained. DAQ acceptance, however, must be improved with respect to the high count rate. It has already been approved by PAC in December 2008; No. S1183: MTV (Mott polarimetry for T-Violation experiment). We will be able to determine R-parameter with the highest precision.

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Current status of SAMURAI

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This report describes the current status of SAMURAI. SAMURAI (Superconducting Analyzer for MUlti-particles from RAdio Isotope beam) is a large-acceptance multi-particle spectrometer to be constructed in RIBF. A schematic illustration of SAMURAI is shown in Fig. 1. The main part is a large-gap (80 cm) superconducting dipole magnet with maximum 7 Tm bending power for momentum analysis of heavy projectile fragments and projectile-rapidity protons with large momentum and angular acceptance. The large gap also enables measurement of projectile-rapidity neutrons with large angular acceptance in coincidence with heavy projectile fragments.

SAMURAI can be used in a variety of ways in experiments with the RI beams provided from BigRIPS. In the breakup experiments of neutron-rich and proton-rich nuclei, SAMURAI's large acceptance enables efficient heavy ion (HI)-neutron and HI-proton coincidence measurements required for invariant-mass spectroscopy. SAMURAI is also suitable for missing-mass spectroscopy, in which measurement of charged particles after the reaction provides not only tagging of the reaction channels but also helps explore the decay modes thanks to the multi-particle detection capability. SAMURAI is also used to scrutinize scattering reactions of light nuclei, such as polarized deutron scattering on proton, in order to study fundamental nucleon-nucleon interactions including three nucleon force effects. We also plan to install a time projection chamber in the large gap of SAMURAI magnet, which is used mainly for reaction studies such as investigation of the density dependence of the asymmetry term of the nuclear equation of state.

The construction budget was approved in this fiscal year. The budget is funded for four years from this fiscal year, and covers the magnet and most of the detectors. Although construction is expected to finish in the fourth year, all contracts relating to the budget must be concluded in this fiscal year due to unavoidable clerical constraints. Therefore, we concluded the contracts for the superconducting dipole magnet, detectors of HI, neutrons, and protons, superconducting triplet quadrupole magnet for beam transport, and required peripheral equipments.

The superconducting dipole magnet is designed to have a maximum bending power of 7 Tm, providing a rigidity resolution of about 1/700 (rms) at 2.3 GeV/c,
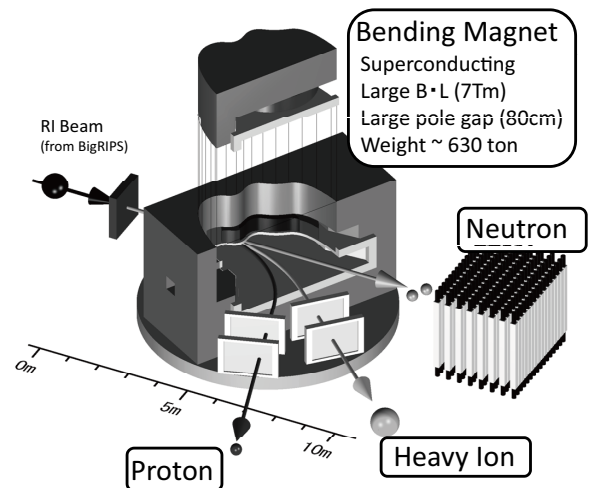
Fig. 1. Schematic image of SAMURAI system. SAMURAI consists of a large bending magnet with surrounding particle detectors. The magnet is a superconducting dipole magnet with a large bending power of 7 Tm and a large pole gap of 80 cm. The heavy ion detectors, neutron detectors, proton detectors, are installed around the magnet. The detector configuration changes depending on the experimental requirements.

particle identification up to $A = 100$, and a large pole gap of about 80 cm, providing vertical angular acceptance of projectile rapidity neutrons of ± 5 degrees. The current design is an H-type magnet with cylindrical poles 2 m in diameter, and round superconducting coils around both poles, each with magnetomotive force of about 2 MAT at maximum, resulting in 3 T central magnetic field. The outer size of the magnet, including the upper, lower, and side yokes, is about 6.8 m in width, 4.6 m in height, and 3 m in depth, and the total weight amounts to about 630 ton. Four field cramps are attached outside of the coils to reduce the fringe field, so that the detectors work beside the magnet. The entire magnet is placed on a rotatable stage to allow maximum flexibility in experimental configurations.

Magnet construction will start in October 2009, and finish early in 2011. The detectors will be constructed in parallel. After some tests and commissionings, the first SAMURAI experiment is scheduled to perform in summer 2011.

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Plan of measurement of $\vec{d}p$ scattering at RIBF

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[Three nucleon force, polarized deuteron, few nucleon system]

Study of three nucleon forces (3NFs) is important in clarifying nuclear phenomena. In addition to the first signals of the 3NF effects in the binding energies of the ^{3}H and ^{3}He, the significance of 3NFs has been recently pointed out for descriptions of discrete states in heavier mass nuclei. Three nucleon scattering at intermediate energies ($E/A \sim 200$ MeV) is one attractive approach to investigate the dynamical aspects of 3NFs, such as momentum and/or spin dependences. An experimental program with polarized deuterons beams at intermediate energies at RIBF is, as a first step, a complete set of deuteron analyzing powers (A_y, A_{yy}, A_{xx}, A_{xz}) in deuteron–proton (dp) elastic scattering at 250 A MeV.

Schematic view of the experimental setup is shown in Fig. 1 (Details reported in Ref.[1]). The vector and tensor polarized deuteron beams are provided by the polarized ion source and they are accelerated by the AVF, RRC and SRC through the IRC bypass transport beam line[1]. The spin symmetry axis of deuteron beams are controlled by the Wien Filter prior to acceleration[2]. Single turn extractions are required for the three cyclotrons to maintain polarization amplitudes during acceleration.

The detection setup BigDpol has been installed at the extraction beam line of the SRC (See Fig. 2). The BigDpol consists of the target chamber, the alumina cone window with 2mm thickness and detector holders. Four pairs of plastic scintillators (BC408) coupled with photo-multiplier tubes (H7415) are placed symmetrically in the directions of azimuthal angles to left, right, up and down. The opening angle of the BigDpol is 10°–70°. The deuteron beams bombard a polyethylene (CH$_2$) target in the scattering chamber. The scattered deuterons and recoil protons are detected in a kinematical coincidence condition by each pair of detectors. The deuteron beams are stopped in a Faraday cup placed at the focal plane F0 of the BigRIPS spectrometer. The beam polarizations are monitored with the beam line polarimeter, Dpol, prior to acceleration by the SRC. The Dpol is placed along the IRC bypass transport beam line[1].

The experiment is scheduled in April, 2009.
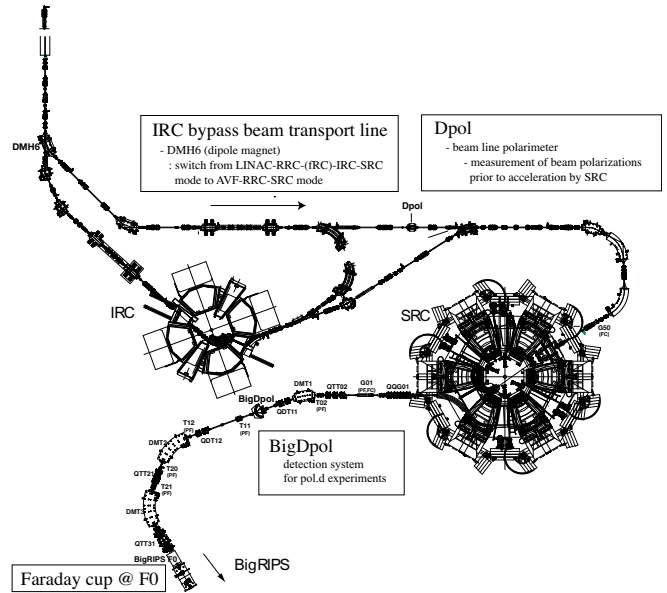
Fig. 1. Schematic view of the experimental setup for elastic dp scattering with polarized deuteron beams.
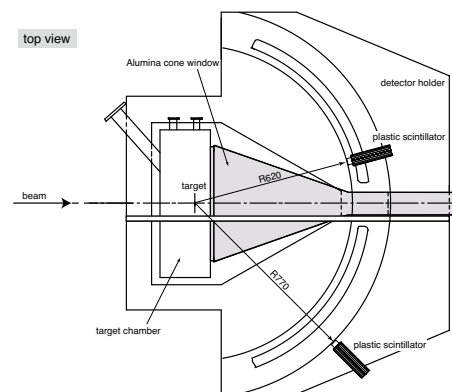
Fig. 2. Top view of the BigDpol.

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Probing Asymmetric Nuclear Matter at RIBF

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[EOS, centrality filter, pion range counter]

As reported in the last year progress report[1] we have been developing a portable centrality filter and a pion range counter aiming to measure $Y(\pi^-)/Y(\pi^+)$ yield ratios in central nucleus-nucleus collisions at intermediate enegies. Detailed studies of pion production should provide meaningful constraints on the density dependence of the symmetry energy at high densities $\rho > \rho_0$ where present constraints are least stringent.

This year we have increased the total number of plastics in the range counter to 12 as shown in Fig.1(left). As read-out phototubes we used either HAMAMATSU H1049-51's or H2431-50's with fast clipping of their anode signals. We have also completed the assembly of a centrality filter consisted of 60 slabs of $5 \times 5 \times 78$ mm^3 plastic scintillators read by two HAMAMATSU H8500 flat-panel multianode-PMTs (Fig.1(right)).
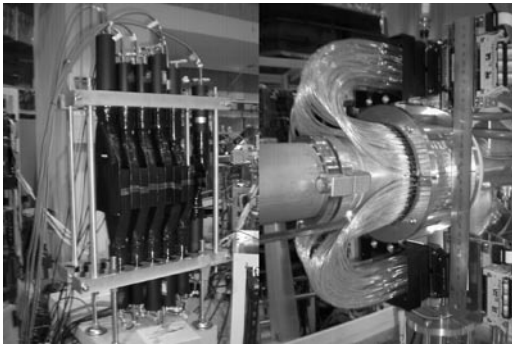
Fig. 1. Pictures of pion range counter(left) and centrality filter(right).

They are tested at HIMAC by measuring low-energy pion production in bombardments of 400 MeV/nucleon ^{132}Xe beam on In. The typical beam intensity was 1×10^6ppp and the target thickness was 330 mg/cm^2. Signals are processed mainly by a FPGA module, QDC's and multi-hit TDC's and accumulated by a Linux PC.

Figure 2 shows a typical particle identification spectrum obtained with the 3rd and 4th elements of the pion range counter. Clear separations among electrons, pions, protons, deuterons, and tritons (from left to right) were observed in the spectrum. It should be noted that there are appreciable amount of backgrounds around pion peak.
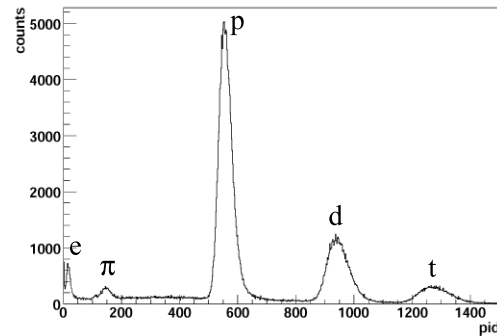
Fig. 2. Particle Identification Spectrum obtained by the pion range counter.

In Fig.3 we show a charged-particle multiplicity distribution associated with charged particles emitted toward 45° compared with an inclusive one. The charged particle-associated one seems strongly peaked at high multiplicity. Detailed analysis using these data is in progress.
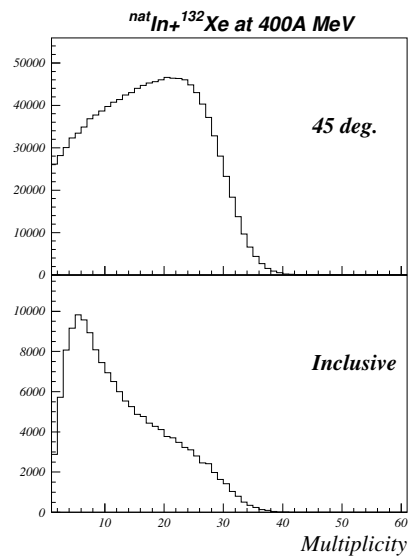
Fig. 3. Charged-particle multiplicity distributions for 45° charged particles in 400 MeV/N In+^{132}Xe collisions (top). Inclusive one is also shown at the bottom.

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The development of the Gamma ray detectors in BigRIPS and Zerodegree spectrometer.

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[BigRIPS, Zerodegree, Particle Identification, Isomer]

The observation of γ-rays emitted from isomeric states was very important for the particle identification in the BigRIPS experiment. In the same way, the observation of γ-rays is also important in the case of the Zerodegree spectrometer (ZDS). In this report, the present status of the development of the γ-ray Ge detector (Clover) in BigRIPS and ZDS is reported. The list of the isomeric states observed in the ZDS commissioning and new isotope search experiment, conducted in November 2008 (ZDS comm/Newiso exp.) is attached at the end of this report.

As in the previous report[1], two Clovers were installed at the 7th focal plane of BigRIPS (F7) as beamline detectors. This system was replaced by a more refined version. Figure 1 shows the picture of the system at F7. Three points are especially important for this new system. First, the additional chamber (Ge chamber) was installed in the downstream of F7 chamber. This chamber has two thin (1.5mm) aluminum windows for γ-ray measurement and a mechanism for the moveable beam stoppers. It became possible to transfer beams to the ZDS area maintaining the beamline vacuum. The moveable beam stopper mechanism is designed to put on two stoppers of different types. Second, the individual stages for two Clovers were installed at both sides of Ge chamber. Taking in and out the Clovers has become very easy because these stages were designed to introduce Clovers on the linear rails. These stages were for Clovers, but small portable type Ge detectors were also able to be installed. Lastly, the automatic Liquid Nitrogen filling device was re-

fined. The older version had a serious problem causing noises in signals on detectors' outputs. In the new version, this problem was overcome by replacing the thermometer, shielding on the electrical wires, etc. This device's ability has already been tested in the ZDS comm/Newiso exp. at the eleventh focal plane of ZDS (F11). Almost zero instances of noise were achieved.

In the case of ZDS, three Clovers were installed approximately 1500mm downstream of F11 chamber. Figure 2 shows the geometrical setup. This stage can install four Clovers in total, from both beamline sides of horizontal and vertical directions. In addition, the stage can be used not only for the F11 with 2m height beamline but also for the other focal planes with 1.7m height beamline such as F7 and F12. Two lead bricks were installed 190mm upstream of Clovers with a 100mm interval in order for the collimation so that the beams will not directly hit the Ge crystals.

In the ZDS comm/Newiso exp., two Al stoppers were prepared with different thicknesses in order to stop the produced charged particles efficiently. One has 10mm effective thickness along the beam axial direction, another has 30mm. In order to observe the γ-rays from three directions efficiently, stoppers have special shapes. Their typical figure is shown in fig. 3. As stoppers are completely symmetrical for horizontal direction and vertical direction, it is possible to obtain the same γ-ray photopeak efficiency for every Clover. In addition, a more effective rotation angle was performed than a 45 degree tilted stopper which had the same effective thickness along the beam axial direction. For this reason, it was possible to design the thickness of aluminum plate itself relatively thinner, and attenuation of γ-rays within the stopper was decreased. According to the Monte Carlo simulation using the Geant4 simulation program code (GEANT), 30% improvement of photopeak efficiency was obtained. The typical photopeak efficiency was 3% for 10mm stopper, and 2.3% for 30mm stopper for 1000keV γ-rays. The efficiency curve is shown in fig. 4. The dotted points represent the calibration result by the ^{152}Eu standard gamma source and curved lines represent the simula-

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tion result by the GEANT.
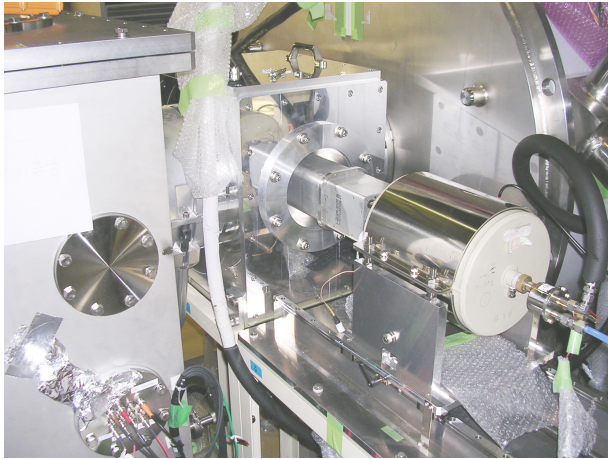
Fig. 1. The setup of the Clovers at F7.
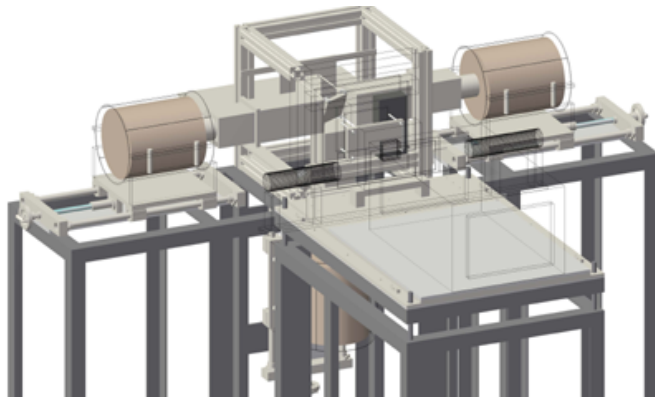
Fig. 2. Geometrical setup of the Clovers at F11.
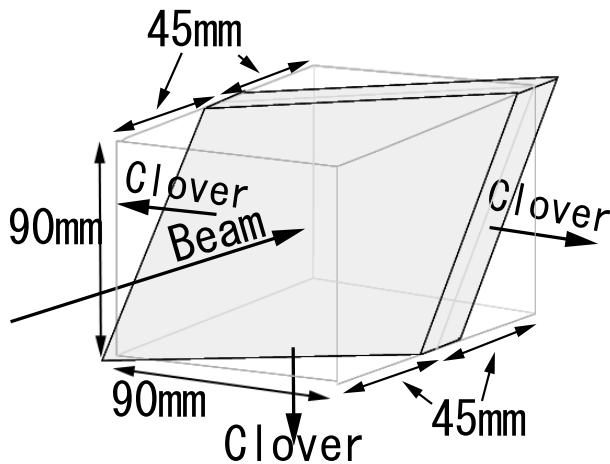
Fig. 3. The stopper shape. Cut under special direction to obtain complete symmetry for horizontal axis and z axis.
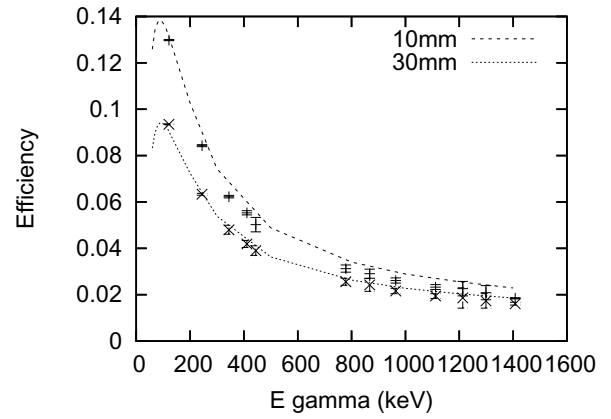
Fig. 4. The total photopeak efficiency curve of F11 three Clovers. The upper line for 10mm stopper and the lower line for 30mm stopper. The curved lines were the GEANT.

Table 1 shows the list of the known isomeric states which were observed in the latest experiment. Several indications of new isomeric states were also seen in that experiment. More precise analysis is now in development.

Table 1. The list of observed isomeric states in the experiment of the ZDS commissioning and the new isotope search in 2008 November.

Nucleus	E_γ(keV)	Half Life(ns)
^{54}Sc	110	7000(5000)
^{60}V	99, 103	320(90)
^{67}Fe	367	43(30)
^{76}Ni	144, 354, 930, 992	590(180)
^{78}Zn	144, 730, 890, 908	319(9)
^{92}Br	97, 106, 155	—
^{95}Kr	84, 113	1400(20)
^{96}Rb	122, 240, 300	2000(100)
^{98}Sr	71, 144	25(2)
^{100}Sr	129, 288, 1202	85(—)
^{117}Ru	80, 101, 126, 184	—
^{120}Rh	98	—
^{121}Pd	134	—
^{124}Ag	75, 156, 304	—
^{125}Ag	714, 670	—
^{127}Cd	739, 771, 821, 909	—
^{128}Cd	237, 439, 537, 645, 783	—
^{130}Cd	128, 138, 539	220(30)
^{129}In	334, 359, 995, 1354	8500(500)
^{130}In	389	<6000
^{129}Sn	570, 1136, 1324	2400(200)
^{130}Sn	391	1600(150)
^{131}Sn	158, 173	300(20)
^{132}Sn	132, 300, 374, 4040	1980(50)
^{134}Sn	174, 347	80(15)
^{136}Sb	173	480(10)

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Measurement of double helicity asymmetry in direct photon production in $p + p$ at $\sqrt{s} = 200$GeV

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The primary goal of the RHIC-PHENIX spin program is to measure the gluon spin component of the proton. The polarized $p + p$ collider is the only way to access it in leading order interaction. Among many final states, the direct photon production is the simplest process and believed to be a golden channel. In contrast to the measurement of neutral pions,[1] it is more sensitive to the sign of gluon polarization. The PHENIX detector[2] has fine segmented electromagnetic calorimeters and is suitable for photon measurements. The direct photon cross section is measured and the NLO theoretical calculation describes the result.[3]

In this report, double helicity asymmetry results are shown from the Run5 (2005, $\int Ldt = 2.5pb^{-1}$, pol=45%) and Run6 (2006, $\int Ldt = 7.0pb^{-1}$, pol=57%) data sets.

Because it is not possible to identify the direct photon on an event base, we calculate the asymmetry of the inclusive photons (A^{raw}) and subtract the background asymmetry (A^{BG}) using the following formula.

$$A^{sig} = \frac{A^{raw} - rA^{BG}}{1-r}, \sigma_{A^{sig}} = \frac{\sqrt{\sigma^2_{A^{raw}} + r^2\sigma^2_{ABG}}}{1-r}.$$

To improve the purity (lower r), an selection of events with small energy activities around the target photon (= isolation cut) is applied. The cut keeps more than 80% of direct photon events for the region of p_T higher than 7 GeV/c.[3] The background asymmetry was estimated with π^0 decay photons which pass the isolation cut in case the partner photon is missed. Fig.1 shows the double helicity asymmetries as a function of p_T. The curves are theoretically calculated based on the GRSV model.

Thanks to improvement in the figure of merit ($\equiv LP^4$), the uncertainty is much reduced in Run6. The uncertainties do not change so much as a function of p_T, because the isolation cut is more effective in the high p_T region.

In leading order, the double helicity asymmetry (A_{LL}) and the gluon polarization ($\Delta G/G$) are connected by $\Delta G/G = A_{LL}/A_1^p/\hat{a}_{LL}$, where A_1^p is the proton spin asymmetry from polarized DIS experiments representing the quark polarization, and $\hat{a}_{LL}$ is the helicity asymmetry in the partonic level. The kinematics are defined by the initial parton momentum and the angle of the outgoing photon. $\Delta G/G$ is obtained by using a proper PDF set and requiring photons in the PHENIX acceptance. Fig. 2 shows the points from the Run5 and Run6 measurements and theoretical curves with different integrated gluon polarization

with a model at $Q^2 = 10$GeV^2.

In summary, we measured the double helicity spin asymmetry of direct photon production in $p + p$ at $\sqrt{s} = 200$ GeV. The measurement from Run6 data is much improved over the previous Run5 result. According to the beam use request, we are going to accumulate $25pb^{-1}$ with 70% polarization in a few years. With that data, the constraint on the gluon polarization in the proton will be improved significantly.

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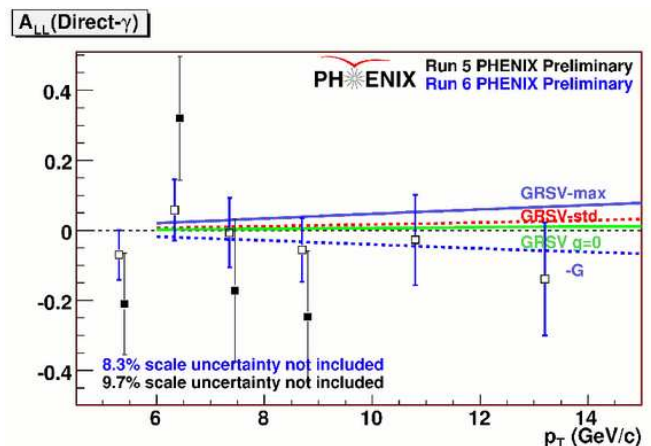
Fig. 1. Double helicity asymmetries of direct photon production. Curves are theoretical calculations.
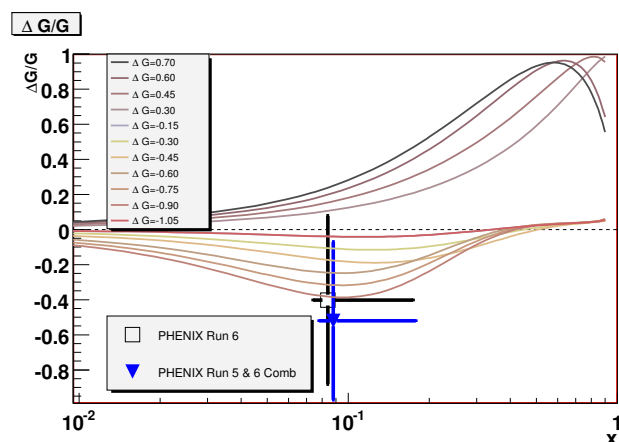
Fig. 2. $\Delta G/G$ as a function of x_{Bj}. Theoretical curves correspond to different ΔG values.

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W-physics with Inclusive Muons in PHENIX: Detailed Feasibility Studies[†]

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[Spin physics, PHENIX, Parity violation]

W production will provide the first direct (flavor separated) measurement of the spin dependent quark and anti-quark-distributions for up- and down-quarks in the proton. The high energy scale set by the W-mass makes it possible to extract quark- and anti-quark polarizations from inclusive lepton spin asymmetries in W-production with minimal theoretical uncertainties[1]. Real W production selects the quark flavors through their charge and it also selects only one helicity of nearly massless quarks due to the maximally parity violating weak interaction. Building the single spin asymmetry of count rates of Ws originating from protons with spin parallel and anti-parallel divided by their sum, $A_L^W = \frac{1}{P} \times \frac{N^+(W)-N^-(W)}{N^+(W)+N^-(W)}$, is then proportional to the helicity distribution $\Delta q(x)$ as in

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}.$$

and similarly for W^- by exchanging u and d.

The inclusive W measurement in PHENIX will be based on muons with $P_T > 20$ GeV in the PHENIX forward arms[2,3]. We have carried out detailed GEANT based Monte Carlo studies followed by full track reconstruction to evaluate the following backgrounds:

– punch through of high P_T hadrons through the magnet yoke upstream of the muon spectrometer and through the hadron absorber in the downstream muon identification system: these hadrons will be reconstructed with approximately correct high momentum.

–punch through of low P_T- hadrons through the magnet yoke and subsequent decay in the muon spectrometer magnet: these hadrons occasionally can be reconstructed incorrectly with high momentum.

– high momentum decay muons, and high P_T cosmic rays. The simulations includes the full detector response with momentum smearing and realistic inefficiencies in reconstruction and acceptance. The momentum smearing is shown in Fig. 1 as function of the true generated transverse momentum. We have identified punch through hadrons that undergo decay as the dominant source of (false) high P_T background. Using optimized standard cuts that have been developed for single muon analysis in PHENIX we find a signal to background ratio of 1/3. Adding an additional hadron absorber of 30cm thickness improves the signal to background ratio to 3/1. Figure 2 shows the expected precision based on full detector simulation, smearing, 70%

polarization and 30cm of additional absorber as compared to current polarized parton parameterizations (see[1] for an overview) as implemented in the RHIC-BOS[4] generator. Additional studies are presently under way to develop a further optimized set of single muon cuts for $P_T > 20$ GeV.

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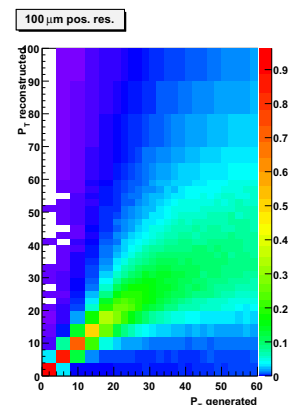
Fig. 1. Momentum smearing matrix for muons with nominal position resolution in the muon tracking system.
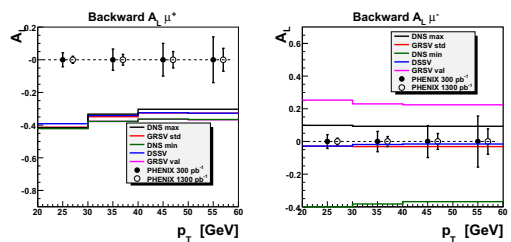
Fig. 2. Expected single spin asymmetries for inclusive leptons from W decays as a function of the reconstructed P_T at backward rapidities as described in the text.

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Measurement of Collins Asymmetry in e^+e^- Annihilation at Belle.[†]

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[Fragmentation, Transverse Spin, Collins Effect]

We have carried out the first measurement of spin dependent effects in the formation of hadrons from quarks that are transversely polarized. Spin effects were observed in the annihilation of electron-positron pairs into inclusive pairs of hadrons in Belle. Spin effects in quark fragmentation were first proposed by Collins[1] in an attempt to describe the large spin asymmetries observed in proton-proton collisions with transverse polarization in the E704 experiment [2]. Collins proposed that the asymmetries observed in E704 arise from struck quarks in hard scattering processes that have their spins aligned (or anti-aligned) with the transverse proton spin. Spin dependent effects in the fragmentation then would give rise to the left-right asymmetries observed in $p+p \longrightarrow \pi^+, \pi^0, \pi^-$ in E704. Collins predicted related spin asymmetries in deep inelastic scattering with leptons of transversely polarized targets. This effect was discovered by the HERMES collaboration at DESY[3]. Boer, Jakob and Mulders first discussed azimuthal asymmetries from Collins fragmentation in hadron production in e^+e^- annihilation[4]. A detailed description of the phenomenology of these asymmetries has been created by Boer[5]. The present Belle experimental effort originates from a RBRC workshop on transverse spin asymmetries in 2000[6]. At the workshop the plan was formulated to extract quark transversity distributions and Collins fragmentation functions from the global QCD analysis of spin asymmetries accessible in polarized semi-inclusive deep inelastic scattering, polarized proton-proton scattering and electron-positron annihilation.

We present here the final result of the Collins asymmetries observed at Belle. The measurement has been carried out on a data sample of $\int Ldt = 547 fb^{-1}$ of inclusive charged pion pairs: $e^+e^- \longrightarrow \pi + \pi + X$. The analysis has been based on events with two-jet topology observing the azimuthal back-to-back correlation of two pions in opposite jet-hemispheres. The results for the Collins $\cos(\phi_1 + \phi_2)$ coefficients, A_{12} observed in so-called hadron double ratios are shown in figure 1. For details refer to our results[7] and[8].

The first combined analysis of Collins asymmetries from deep inelastic scattering and Belle has been recently carried out by Anselmino and collaborators [9]. The resulting Collins fragmentation functions and quark transverstiy distributions are shown in figure 2.

It is found that quark transversity distributions in the proton are sizable and that there a significant spin effects in the fragmentation of transversely polarized quarks into pions.

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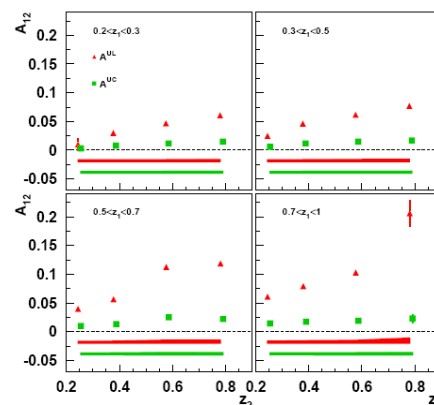
Fig. 1. Collins asymmetries observed in $e^+e^- \longrightarrow \pi\pi + X$ at Belle, see reference[3].
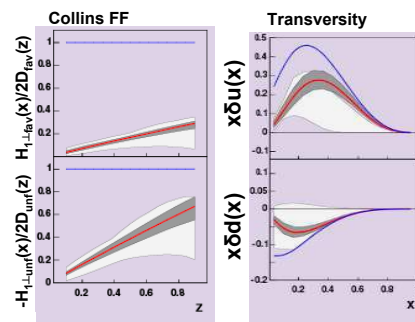
Fig. 2. Collins fragmentation function extracted from semi inclusive deep inelastic scattering data and $e^+e^- \longrightarrow \pi\pi + X$ at Belle, see reference[4].

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Precision Measurements of Hadron Multiplicities in e^+e^- Annihilation at BELLE[†]

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[Precision hadron multiplicities, fragmentation functions, BELLE]

1 Measurement Description

This paper summarizes the status of precision measurements of $\pi^{+,-}$, $K^{+,-}$, π^0 and η multiplicities in e^+e^- annihilation at a center of mass energy of 10.52 GeV at the BELLE experiment at KEK, Japan[1]. The hadron multiplicities are measured as a function of z which is the hadron energy relative to half of the center-of-mass energy in electron-positron annihilation into quark-antiquark pairs. The measured multiplicity distributions are corrected for particle misidentification and acceptance effects.

2 Motivation

Multiplicity measurements at Belle are motivated by two recent studies describing the extraction of unpolarized fragmentation functions[2,3]. Fragmentation functions describe hadron production from a final-state quark or gluon in processes such as hadron collisions, electron-positron annihilation and deep inelastic scattering of leptons on protons or nuclei. The present measurements are intended to provide high precision datasets as an input to the extraction of fragmentation functions, and thereby significantly lower the uncertainties of the extracted fragmentation functions. Precise knowledge of fragmentation functions is required for the extraction of the gluon helicity distribution from spin asymmetries measured in hadron collisions at the Relativistic Heavy Ion Collider (RHIC)[4].

3 Measurement Status and Outlook

For charged hadrons, experimental particle yields need to be corrected for particle misidentification. A detailed study to determine particle identification (PID) probabilities for $e^{+,-}$, $\mu^{+,-}$, $\pi^{+,-}$, $K^{+,-}$ and $p, \bar{p}$ has been carried out. A linear model has been developed for the correction of measured yields for particle misidentification. This correction changes significantly the measured charged particle distributions at the order of 5 to 10% for pions and 10 to 35% for kaons. The yields of neutral hadrons π^0 and η are measured via the two photon decay process.

Hadron multiplicities are presently extracted for

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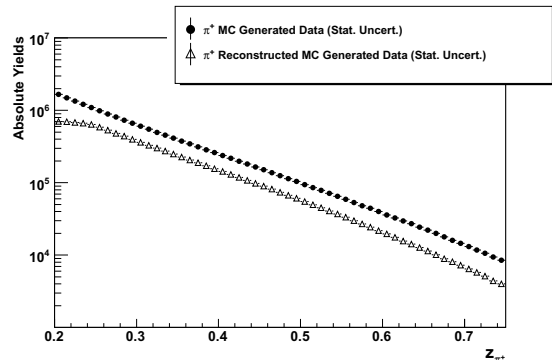
Fig. 1. Yields of π^+ from Monte Carlo against the normalized hadron energy z_{π^+}. Closed circles show yields generated with PYTHIA. Open triangles indicate yields after detector response simulation and reconstruction. The difference between the plots shows the magnitude of the PID and acceptance correction.

normalized hadron energies z within $0.2 < z < 0.75$ and a bin width of $\Delta z = 0.01$. Fig. 1 shows π^+ yields against the normalized hadron energy z. Shown are the yields generated with the Monte Carlo event generator PYTHIA[5] and the yields after a GEANT-based[6] detector response simulation and reconstruction. Eventually, the measurement will be extended to higher values of z and the systematic uncertainty analysis for PID, momentum smearing and acceptance effects will be finalized. The leading uncertainty is expected to arise from the systematic uncertainties connected with the PID correction. The overall systematic uncertainties are expected to remain below 3% (5%) for π (K) spectra at low to mid $z < 0.6$, and to increase with z up to 5% (17%) for π (K) spectra, respectively.

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Measurement of Interference Fragmentation Functions at Belle[†]

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[Nucleon structure, Fragmentation, Interference fragmentation function, Transversity]

Measurements of azimuthal asymmetries in hadron pair correlations at Belle allow access to the chiral odd dihadron interference fragmentation function (IFF). The IFF describes the production of a hadron pair from a transversely polarized quark. The transverse spin of the fragmenting quark leads to an anisotropy in the azimuthal distribution of the final state hadron pair. This makes it possible to use IFF-processes as quark polarimeter. That makes it very important for the measurement of the so-called transversity distribution function which describes the transverse spin structure of the nucleon. Interference Fragmentation therefore offers an alternative way to access quark transversity distributions in hard scattering processes off transversely polarized nucleon targets[1]. Recently, the single hadron Collins fragmentation process has been used for a first determination of quark transversity distributions and Collins fragmentation asymmetries have been measured in Belle[2]. In comparison to Collins fragmentation, the IFF exhibits some favorable features that are unique to the fragmentation into two hadrons. Because the second hadron provides an additional degree of freedom, the asymmetry survives an integration over transverse momenta. This allows for collinear factorization, model independence and easier evolution of the results to center of mass energies of complementary fixed target experiments.

At Belle unpolarized electrons and positrons annihilate at a center of mass energy of 10.58 GeV for measurements on the $\Upsilon(4S)$ resonance and 10.52 GeV for measurements of the continuum background. The produced quark - antiquark pairs will have antiparallel spin configurations with a transverse component proportional to $\sin^2\theta$, where θ is the angle between quark and electron axis in the center of mass system. The measurement is carried out in a sample with back to back di-jet geometry using a thrust selection of $T > 0.8$. The measurement consists of observing hadron pairs simultaneously in both jet-hemispheres and correlating the angular distribution of the hadron planes on both sides: If $\mathbf{R_j} = \mathbf{P_{h1}^j} - \mathbf{P_{h2}^j}$, with $\mathbf{P_{hi}^j}$ the momentum vectors of the hadrons in hemisphere $j \in \{1,2\}$, then the count rate is dependent on the azimuthal angle ϕ_j between $\mathbf{R_j}$ and the spin vector around the momentum of the fragmenting quark approximated by the thrust axis. The electron and positron beams in KEKB are unpolarized and therefore the ϕ_j dependence of the hadron planes would average out in an inclusive single hemisphere measurement. However, the correlation between $\mathbf{R_1}$ and $\mathbf{R_2}$ remains and leads to a dependence of the count rates on the angle $\phi_1 + \phi_2$. Figure 1 shows the projected sensitivities for charged pion pairs using the data collected off-resonance. The precision allows for significant asymmetries according to various model predictions[3,4,5]. Furthermore on-resonance data, a factor 10 more abundant than the off-resonance data, will be used for this analysis. The anticipated Belle IFF results will improve the understanding of spin dependence in hadron formation and provide an important tool for the study of transverse nucleon spin structure.

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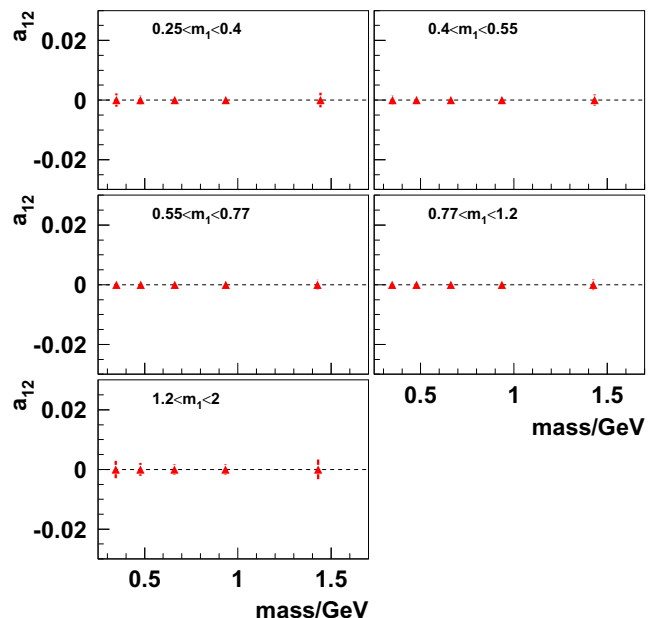
Fig. 1. Sensitivity projections for Belle measurements of charged pion IFF measurements using 55 fb^{-1}. The correlation asymmetries are shown as function of the pion pair invariant mass.

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Double Helicity Asymmetry of Inclusive Charged Hadrons in *pp* Collisions at $\sqrt{s} = 62.4$ GeV at PHENIX

D. Kawall,[*1,*2] and A. Datta[*2]

[Double Helicity, Asymmetry, Longitudinal Polarization]

Introduction

In 2006, the PHENIX collaboration at the Relativistic Heavy Ion Collider (RHIC) recorded ≈ 50 nb^{-1} of longitudinally polarized *pp* collisions at $\sqrt{s}$=62.4 GeV/*c*. We have analyzed these data to extract the double longitudinal spin asymmetry, $A_{LL}(pp \rightarrow h^{\pm}X)$ for unidentified, inclusive charged hadrons $h^{\pm}$ at midrapidity, $|\eta| < 0.35$, with p_T from 0.5 to 4.5 GeV/*c*. The production of hadrons with $p_T > 1$ GeV/*c* is dominated by quark-gluon scattering, and so is sensitive to the polarized gluon distribution, $\Delta g(x)$, for momentum fraction $x \approx 0.05 - 0.2$[1].

Event Selection and Systematic Checks

We analyzed *pp* collisions selected with the minimum bias trigger for charged tracks in the PHENIX drift chamber (DC)[2]. These track were extrapolated to the outer pad chamber, PC3[2], where we required closely matching hits. Fiducial cuts were applied, as were corrections for offsets of the beam and DC affecting the extraction of the particle p_T from the DC track angle.

Several backgrounds were present in this set of events. Electrons/positrons from γ conversion, (γ from π^0 or η decay) were rejected by placing a veto on the PHENIX Ring Imaging Cherenkov[2], which detects $e^{\pm}$ above 20 MeV, and $\pi^{\pm}$ above 4.7 GeV. Particles originating from long-lived particles ($\pi^{\pm}$, $K^{\pm}$, K_L^0) decaying far (> 20 cm) from the primary vertex, typically don't pass the tight DC-PC3 matching cuts. Short lived-particles (K_s^0, Λ, Σ, Ξ, ...) decaying close to the vertex, yield particles that pass the cuts, and comprise $\approx 7\%$ of the sample.

Each resulting double spin asymmetry was checked for errors by constructing the single spin, parity-violating asymmetry A_L (which was consistent with zero), randomizing the bunch polarizations, and by checking for the consistency of A_{LL} extracted separately from each detector arm, and from different fills.

Results and Predictions From Theory

Preliminary results are shown in Fig. 1 with next-to-leading order perturbative QCD calculations based on different polarized gluon distributions[3].
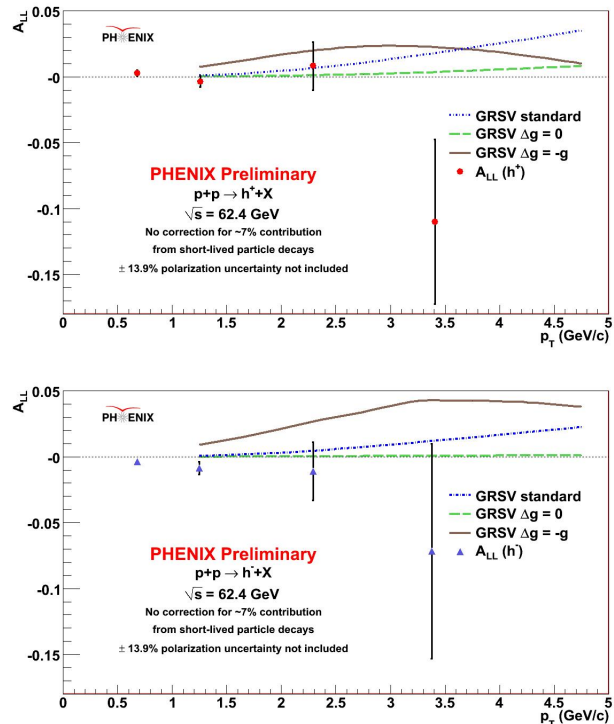
Fig. 1. GRSV predictions and preliminary results for $A_{LL}(pp \rightarrow h^+ X)$ (upper) and $A_{LL}(pp \rightarrow h^- X)$ (lower).

Discussion

The statistical precision of the results is impressive, well below 10^{-2} in the first two p_T bins. The results can be used to exclude the GRSV models, $\Delta g(x) = -g(x)$ and $\Delta g(x) = g(x)$ (which has $A_{LL} > 0.1$ at p_T of 4 GeV/*c*, too big to show on the plot).

It is interesting to note that when qg scattering dominates, we expect $A_{LL}^{\pi} \propto \Delta g \left(\Delta u D_u^{\pi} + \Delta d D_d^{\pi} \right)$. Then, since Δd is large and negative, Δu is large and positive, $D_u^{\pi^+} > D_d^{\pi^+}$, and $D_u^{\pi^-} < D_d^{\pi^-}$, if $\Delta g(x) > 0$ we'd expect $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$. We can't discern such an ordering from this data, which is consistent with Δg being small and/or $\Delta g(x)$ having a node.

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PHENIX local polarimeter analysis in polarized proton-proton collisions at $\sqrt{s} = 200$GeV from RHIC Run-8

S. Dairaku[*1] for the PHENIX Collaboration

[Spin, asymmetry]

In RHIC Run-8 proton-proton collisions, we were focused on transverse-spin physics, and thus collected data on transversely polarized proton-proton collisions. A local polarimeter was used to evaluate whether proton beams were transversely polarized in RHIC Run-8.

A local polarimeter was also used n previous RHIC Runs. One of the main goals of the PHENIX experiment is to determine the polarized gluon distribution function in a proton.[1] To achieve this objective, we have used longitudinally polarized proton-proton collisions. We determine the polarized gluon distribution function by measuring double longitudinal-spin asymmetries during the production of various particles. In RHIC rings, proton beams are vertically polarized. Therefore, we need to change the direction of the beam polarization from the vertical direction to the longitudinal direction using spin rotator magnets. A local polarimeter is also used for evaluating how correctly the proton beams are longitudinally polarized when the spin rotator is on.

When the proton beams are vertically polarized, the local polarimeter can measure the significant single transverse-spin asymmetry (A_N) for forward neutron production,[2] which is calculated by

$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{1}{P} \frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}, \qquad (1)$$

where P is the absolute polarization value measured by the RHIC polarimeters, and $N_{L(R)}^{\uparrow(\downarrow)}$ is the number of neutrons scattered to the left (right) when the direction of the beam polarization is vertically upwards (downwards). We identify forward neutrons using a zero degree calorimeter (ZDC) and measure the scattering direction of the neutrons with a shower maximum detector (SMD) by detecting the shower shape in the ZDC (see figure 1).

Figure 2 shows the azimuthal angle ϕ dependence of the asymmetry A_N for forward neutron production for two RHIC rings (the so-called blue ring and yellow ring, respectively) from RHIC-Run8 data. We can see the clear sinusoidal shape and confirm that the proton beams are transversely polarized.

Figure 3 shows the asymmetry A_N for two RHIC rings versus a fill number which is defined as the period of time encompassing injection, acceleration, and stor-

age of beam in RHIC rings. It shows that the asymmetry A_N did not undergo a lot of changes from fill to fill and the transverse polarization of the proton beam was stable.

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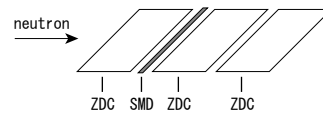
Fig. 1. Schematic layout of the ZDC and the SMD.
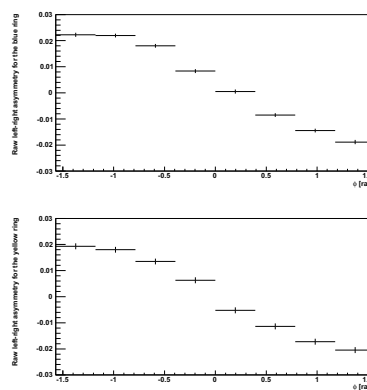
Fig. 2. Azimuthal angle ϕ dependence of the asymmetry for forward neutron production for the blue ring in RHIC Run-8.
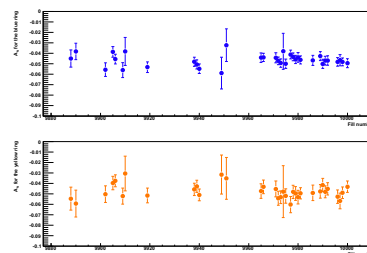
Fig. 3. Asymmetry for forward neutron production for each rings versus a fill number in RHIC Run-8.

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2. Nuclear Physics(Theory)

Covalent isomeric state in ^{12}Be induced by two-neutron transfers[†]

M. Ito,[*1] and N. Itagaki,[*2]

[Transfer reaction, molecular resonance, unstable nuclei]

The experimental techniques producing the slow RI beam are now under development in many facilities, and the scattering of a neutrons' drip-line nuclei, ^{8}He, by an α target has just been measured at GANIL[1]. Since ^{8}He has the $\alpha+4N$ structure with four weakly bound neutrons and an α cluster, during the collision, the valence four neutrons can easily be exchanged between two α-particles. Therefore, the $\alpha+^{8}$He colliding system is the candidate manifesting an isomeric resonance excited by the neutron transfer coupling, and we investigated the resonance structures appearing in the excitation function of the $\alpha+^{8}$He scattering.

In order to investigate the $\alpha+^{8}$He$_{g.s.}$ scattering, the reaction process should be treated consistently with the low-lying bound states of the compound system of ^{12}Be, because the resonances correspond to excited states, which are embedded in the continuum above the particle decay threshold. In ^{12}Be, the molecular orbital (MO) model can successfully describe the low-lying states[2]. In the present study, therefore, the MO configurations and the scattering process must be treated in a unified manner. For this purpose, we apply the generalized two-center cluster model (GTCM)[3,4], which can cover the low-lying MO configurations[2] as well as the scattering states among the ionic ones, the ^{X}He+^{Y}He $(X,Y=4\sim8)$; hence, treating of resonant phenomena in slow scattering is possible.

In GTCM, the total wave function is given by

$$\Psi^{J^{\pi}(+)} = \sum_{\beta} \chi_{\beta}^{(+)} + \sum_{\nu} b_{\nu}\hat{\Psi}_{\nu}^{J^{\pi}} \quad . \tag{1}$$

The first term stands for the "open channels" labeled by β, on which the scattering boundary condition is explicitly imposed[3,4]. Here, $\chi_{\beta}^{(+)}$ denotes the wave functions of two scattering nuclei. We consider three rearrangement channels, $\alpha+^{8}$He$_{g.s.}$, ^{6}He$_{g.s.}$+^{6}He$_{g.s.}$ and ^{5}He$_{g.s.}$+^{7}He$_{g.s.}$ as open channels. The second term stands for the "intrinsic states", and the $\hat{\Psi}_{\nu}^{J^{\pi}}$ labeled by an eigenvalue number ν, is calculated by diagonalizing the total Hamiltonian with basis functions of the atomic orbitals (AOs).

The scattering matrices (S matrices) for the central collision of $\alpha+^{8}$He $(J^{\pi}=0^{+})$ are shown in Fig. 1. In the S matrices calculated from the open channels (dotted curves), there are not any resonant peaks, but we can clearly confirm the formation of the sharp resonant
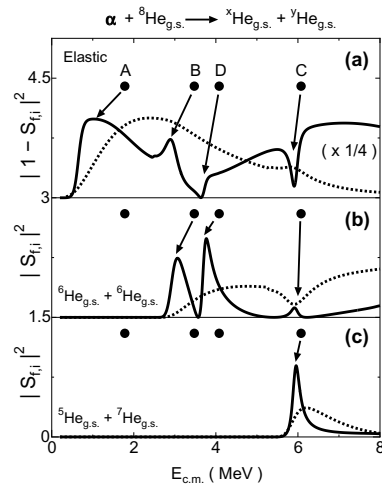
Fig. 1. S matrices for $\alpha+^{8}$He$_{g.s.}$ ($J^{\pi}=0^{+}$). See text for details.

peaks in the full solution (solid curves), in which the intrinsic states (solid circles) are coupled.

The resonances A~C have the ionic configuration of ^{X}He$_{g.s.}$+^{Y}He$_{g.s.}$, while D has a characteristic structure, which is called the covalent SD state. In this configuration, two neutrons occupy the $0p$-wave AO, which is perpendicular to the $\alpha-\alpha$ axis around each α-cluster, like ^{5}He+^{5}He, while the remaining two neutrons form the $(\sigma^{+})^{2}$ bonding. Due to the formation of the σ^{+}-bonding, the $\alpha-\alpha$ distance is increased, and it corresponds approximately to hyperdeformation. The present calculation predicts the strong decays of the covalent SD state into ^{6}He$_{g.s.}$+^{6}He$_{g.s.}$, which are supported by recent observation[5].

It is very interesting to compare the present results with the latest experiment at GANIL[1]. This is the first study pointing out the formation of a covalent isomeric-state via a neutron-transfer reaction, which shall be generally observed in light neutron-rich nuclei and systematic studies are continually proceeding.

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Isoscalar monopole transitions in ^{10,12}Be

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[Nuclear Structure, cluster model, unstable nuclei]

Recent studies strongly suggest that cluster structures can explain the strength of monopole transitions (MTR), in the energy region of E ≤ 10 MeV, which are observed as a discrete strength in the excitation energy. In fact, the enhancements of MTR are confirmed in the nuclear excitations of ^{11}B[1] and ^{13}C[2] by an α target. In addition, a theoretical study clearly demonstrated that the cluster configurations in both the initial and final states strongly enhanced the MTR matrix elements in the $N=Z$ systems, such as ^{12}C and ^{16}O.[3] Therefore, the MTR below E ~ 10 MeV can be considered the guideline of the development of cluster structures, because naive shell models can never describe the enhanced MTR around this energy region.

On the contrary, in light neutron-excess systems, various molecular structures are discussed from the viewpoint of clustering phenomena, and hence investigations of MTR are quite important in the study of neutron-excess nuclei. In particular, strong MTRs are observed in a wide energy range of ^{12}Be. In the transition to the low-lying 0_2^+ (E$_x \sim 2.2$ MeV), an electric MTR is measured through the e^+e^- decays,[4] while in the continuum energy region above the α-decay threshold, strong enhancements of MTRs are observed as discrete resonances, which finally decay into ^{6}He$_{g.s.}$+^{6}He$_{g.s.}$ and α+^{8}He$_{g.s.}$.[5] In this report, we examine the nuclear structures of ^{12}Be=α+α+$4N$ and discuss the enhancement of the monopole transition in connection to the intrinsic structures. We applied the generalized two-center cluster model in which the molecular orbital (MO) configurations and the atomic (ionic) ones with ^{x}He+^{y}He could be described in a unified manner.[6]

First, we calculated the energy spectra (left part in Fig. 1) and investigated the wave functions in individual levels to identify their intrinsic character. The MO configuration of $(\pi_{3/2}^-)^2(\sigma_{1/2}^+)^2$ becomes the ground (0_1^+) state, and the five levels are obtained as the excited states. We found that all the excited states can be characterized in terms of the excitation degree of freedoms. For instance, the 0_2^+ state has $(\pi_{3/2}^-)^2(\pi_{1/2}^-)^2$, and it corresponds to the two particle excitation mode from 0_1^+ with $(\pi_{3/2}^-)^2(\sigma_{1/2}^+)^2$. Furthermore, the 0_3^+ state corresponds to the cluster excitation mode from the 0_1^+ state, in which the relative motion between two α-clusters is strongly excited.

Secondly, we calculated the matrix elements of isoscalar MTR, $| < 0_f^+ | \sum_i^{12} r_i^2 | 0_1^+ > |^2$, and the result
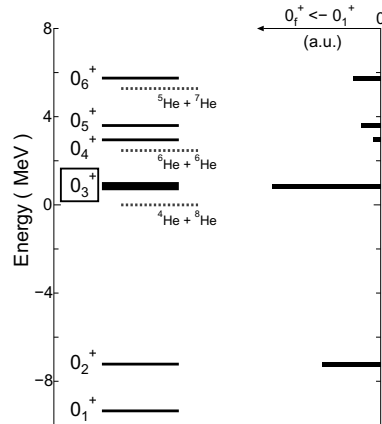
Fig. 1. Energy spectra (left) and monopole strength (right) in ^{12}Be (J^π=0$^+$). Dotted lines represent the threshold energy of the ^{x}He+^{y}He channels.

is shown at right in Fig. 1. As can be clearly confirmed in the figure, MTR to 0_3^+ is the largest of all the excited states, although an enhancement also occurs in the transition to 0_2^+, which is consistent with the observed electric MTR.[4] Therefore, this result strongly suggests that the monopole transition is enhanced when the final state corresponds to the cluster excitation mode from the ground state.

We have also calculated the continuum discretized coupled-channels (CDCC) for the monopole breakup of ^{10}Be into α+^{6}He by a ^{12}C target.[7] This breakup reaction is mainly induced by a nuclear interaction from the target, and the multi-step of the continuum-continuum coupling is quite strong. We confirmed strong enhancement in the transition of $0_1^+ \rightarrow 0_3^+$. The final state corresponds to the cluster excitation mode from the 0_1^+ state. Therefore, the cluster excitation mode is strongly excited in the nuclear breakup reaction, which is consistent with the result in the analysis of MTR for ^{12}Be.

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A smoothing method of discrete breakup S-matrix elements in the theory of continuum-discretized coupled channels[†]

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[Nuclear reaction, unstable nuclei]

The study on neutron-rich nuclei has become one of the central subjects in nuclear physics. Breakup reactions have played key roles in investigating such unstable nuclei. One of the most reliable methods for treating the breakup processes is the method of continuum-discretized coupled channels (CDCC)[1]. In CDCC, breakup continuum states of a projectile are described by a finite number of discretized states, which form a complete set within a finite model space. Consequently, the S-matrix elements calculated with CDCC, $\hat{S}_i$, are discrete in continuum, although the exact ones are continuous. Thus, one needs a way of smoothing $\hat{S}_i$ in order to analyze real breakup processes.

In principle, this is possible by calculating the overlap functions between the exact continuum states and the discretized states. The overlap function called the smoothing factor can be easily calculated in three-body breakup reactions of two-body projectiles, but it is quite hard in four-body ones of three-body projectiles. Very recently, we have proposed a smoothing method applicable to four-body breakup reactions[2], but it still requires heavy numerical calculations.

In this work, we present a simple formula that makes it possible to smooth $\hat{S}_i$ accurately by using the complex scaling method[3], which is a powerful tool for solving many body resonance and weakly bound states[4]. In the formula, the smoothing factor between the discretized state $\hat{\phi}_i$ and the continuum one ψ with a positive energy ϵ is calculated by

$$\langle \hat{\phi}_i | \psi \rangle \approx \langle \hat{\phi}_i | \varphi_0 \rangle$$
$$+ \sum_{jk} \langle \hat{\phi}_i | C^{-1}(\theta) | \phi_j^\theta \rangle \frac{1}{\varepsilon - \epsilon_i^\theta} \langle \tilde{\phi}_j^\theta | V^\theta | \phi_k^\theta \rangle \langle \tilde{\phi}_k^\theta | C(\theta) | \varphi_0 \rangle,$$

where $C(\theta)$ and φ_0 are the scaling transformation operator and the plane wave of constituent particles in the projectile, respectively. The complex scaled states ϕ_i^θ are obtained by diagonalizing the complex-scaled internal Hamiltonian H^θ of the projectile with the L^2-type functions: $\langle \tilde{\phi}_j^\theta | H^\theta | \phi_{j'}^\theta \rangle = \epsilon_j^\theta \delta_{jj'}$, where $\tilde{\phi}_j^\theta$ is a biorthogonal function of ϕ_j^θ. When the Gaussian basis functions are taken in the calculations of $\hat{\phi}_i$ and ϕ_j^θ, the matrix elements $\langle \hat{\phi}_i | C^{-1}(\theta) | \phi_j^\theta \rangle$ and $\langle \tilde{\phi}_k^\theta | C(\theta) | \varphi_0 \rangle$ are analytically obtained. The matrix elements $\langle \tilde{\phi}_j^\theta | V^\theta | \phi_k^\theta \rangle$ are also easily obtained by making a single integral. Thus, this formula is quite useful and applicable not only to three-body but also four-body breakup reactions.

Validity of the formula is tested for two kinds of three-body breakup reactions, ^{58}Ni(d,np) at 80 MeV and ^{12}C(^{6}He,$^2n^4$He) at 229.8 MeV. In the latter, ^{6}He should be treated as the three-body $n+n+^4$He system. However, since our interest is the 2^+ resonance in the present test, we use the dineutron ($^2n+^4$He) model that can describe the 2^+ resonance reasonably well.

Figure 1 shows the squared moduli of breakup S-matrix elements, $S(k)$, as a function of the relative momentum k between two constituent particles of the projectile. Here $S(k)$ is defined as $S(k) = \sum_i \langle \psi(k) | \hat{\phi}_i \rangle \hat{S}_i$. The open circles are results calculated with the exact smoothing factors. The dotted, dashed, and solid lines correspond to results of the new smoothing method at the scaling angle $\theta = 5°$, $10°$, and $15°$, respectively. For both the cases, the breakup S-matrix elements smoothed with the formula tend to the exact ones as θ increases. In a forthcoming paper, we will investigate the practicability of this formula for four-body breakup processes of three-body projectiles.
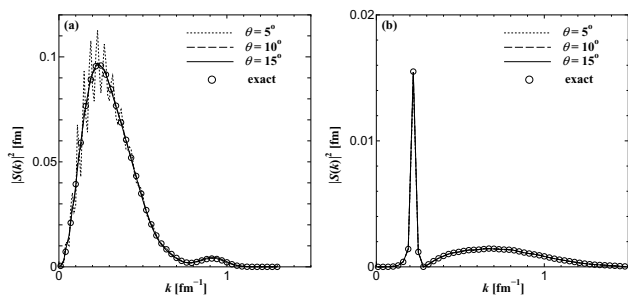
Fig. 1. The squared moduli of breakup S-matrix elements as a function of k for ^{58}Ni(d,pn) at 80 MeV (left panel) and for ^{12}C(^{6}He,$^2n^4$He) at 229.8 MeV.

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Elastic and total reaction cross sections of oxygen isotopes in Glauber theory[†]

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[Nuclear reaction, total reaction cross sections, elastic scattering, unstable nuclei]

Studies on neutron-rich unstable nuclei have been attracting attention both experimentally and theoretically.[1] These studies are motivated, for example, by that we want to understand the nuclear structure and excitation mode of neutron-rich nuclei as well as their role in forming heavy elements in stars. Binding energy, radius and density distribution, among others, are basic quantities for determining nuclear properties. Reactions of unstable neutron-rich nuclei with a proton target are, therefore, of current interest as they are at present a major means to probe the matter densities of exotic nuclei, particularly the region of the nuclear surface. If one appropriately selects incident energies, protons could be more sensitive to the neutron distributions than to the proton distributions of nuclei.

In this work, we systematically calculate the total reaction cross sections of oxygen isotopes, $^{15-24}$O, on a ^{12}C target at high energies using the Glauber theory. We also study the differential elastic-scattering cross sections of p-^{20,21,23}O to examine the sensitivity of the diffraction pattern to the nuclear surface. The oxygen isotopes are described with the Slater determinants generated from a phenomenological mean-field potential containing central and spin-orbit potentials, which is an extension of our previous work for describing carbon isotopes.[2,3] The strength of the spin-orbit potential is set to follow the standard value, whereas that of the central part is chosen so as to reproduce the separation energy of the last nucleon.[2] This prescription is called the "S_n model" hereafter. It apparently ignores the pairing effect, which gives a larger separation energy for the even-N nuclei than for the odd-N nuclei. Therefore, this model tends to predict a too large size for the odd-N isotope. To remedy this problem, we test another one, called the "$\langle S_n \rangle$ model", which fits the average separation energy for the nucleons in the last orbit. The agreement between theoretical and experimental results is generally good, especially in the $\langle S_n \rangle$ model, but the sharp increase of the total reaction (interaction) cross sections from ^{21}O to ^{23}O remains an open question.

As a possible cross section that may depend on the
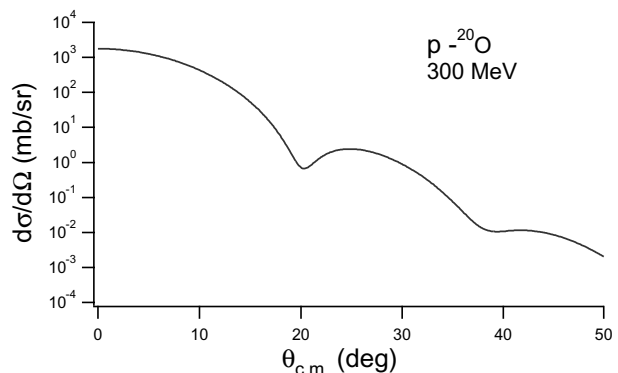
Fig. 1. Prediction of differential elastic-scattering cross section for p-^{20}O at $E_p = 300$ MeV. The curve represents the full calculation with the harmonic-oscillator shell-model wave function.

nuclear radius more sensitively than the reaction cross section, we examine the differential cross sections of the p-^{20,21,23}O elastic scatterings at the incident energy of $E_p = 300$ MeV. For this purpose, we calculate the full Glauber amplitude using harmonic-oscillator wave functions. We prepare two amplitudes: One is obtained using the scale parameter of the wave function to reproduce the numerical result of each matter radius in the $\langle S_n \rangle$ model, the other is obtained using the scale parameter to reproduce the empirical value of each total reaction (interaction) cross section. The differential cross sections calculated from the two amplitudes are found out to be not very different up to the second minimum of the angular distribution.

Finally, we predict the differential cross section for p-^{20}O elastic scattering (Fig. 1), which has recently been measured.[4] Our prediction appears consistent with preliminary data. This implies that it is possible to calculate to a good approximation the total reaction and elastic scattering cross sections at high energies.

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Shell-model description of beta-decays for pfg-shell nuclei

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[NUCLEAR STRUCTURE, shell model, unstable nuclei]

The effective interaction is a key ingredient for successful shell-model calculations. Owing to recent developments in computers as well as novel numerical techniques, the applicability of the shell model is rapidly expanding. On the other hand, our knowledge of the effective interaction is still insufficient especially for cases where more than one major shell should be taken as an active valence space. Such a treatment is essentially important for describing neutron-rich nuclei.

We have developed an effective interaction[1] for shell-model calculations in the model space consisting of valence orbits $1p_{3/2}, 0f_{5/2}, 1p_{1/2}$ and $0g_{9/2}$ assuming an inert ^{56}Ni core (f5pg9-shell). It can be regarded as a first step for future extensions to the pf+sdg model space. Starting from a microscopic interaction (renormalized G-matrix)[2] based on a realistic NN-potential, we have varied 45 linear combinations of Hamiltonian parameters (133 two-body matrix elements and four single-particle energies) by a least-squares fit to the 400 experimental binding and excitation energy data out of 87 nuclei with masses A=63-96. In the latest iteration, we have attained the rms error of 185 keV.

As an application of this interaction, we have evaluated the β-decay properties for N=50 and 49 nuclei, aiming at the analysis of the r-process nucleosynthesis. For understanding the r-process, we need precise information of nuclear properties over a wide mass range under extreme conditions which is not accessible by current experiments. For this purpose, nuclear structure calculations based on the mean-field approximation have been widely used. Such methods are applicable to any nuclei in the nuclear chart, but are not necessarily accurate because only limited correlations can be treated. On the other hand, the shell model can treat any two-body correlations and can give accurate description of nuclear structure, if we can use suitably chosen model spaces and effective interactions.

Because of the strong energy dependence of the phase space factor, low-lying states mainly contribute to the β-decay half-life. The spin-flip decays $\nu g_{9/2} \rightarrow \pi g_{7/2}$ and $\nu f_{5/2} \rightarrow \pi f_{7/2}$ are both out of the present f5pg9-shell model space. Since we consider N=50 and 49 neutron-rich nuclei, the former mode should appear at high excitation energy in the daugh-
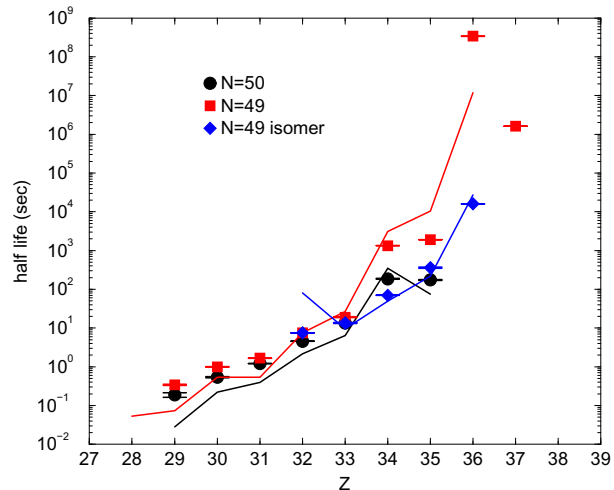
Fig. 1. Comparison of the β-decay half-life between the shell-model results (lines) and experimental data (symbols) for N=50 and 49 nuclei. For N=49 cases, the results for the low-lying isomer are also shown.

ter nucleus and may not be important. On the other hand, the latter mode may be important because it is predicted that, due to the strong repulsive interaction between the $\pi f_{7/2}$ and the $\nu g_{9/2}$ orbit through the tensor force[3], as neutrons occupy the $g_{9/2}$ orbit, the effective single-particle energy gap above the proton $f_{7/2}$ orbit decreases and the excitation from the Z=28 core may be enhanced.

We have calculated the β-decay half-life for the allowed transitions by using the experimental Q-values and the same quenching factor q=0.6 for the evaluation of the Gamow-Teller strength as in Ref.[1]. Shell-model calculations have been carried out in a conventional way by using the code MSHELL.[4] The results are shown in Fig.1. It can be seen that the shell-model results are in reasonable agreement with the experimental data for less neutron-rich nuclei (Z>30) except for ^{84}Br, ^{85}Kr and the isomer state in ^{81}Ge, while for neutron-rich nculei (Z<30), the shell-model predictions systematically underestimate the experimental values. This result may indicate the importance of an explicit treatment of the Z=28 core excitation.

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Skyrme-QRPA calculation for exotic modes in neutron-rich Mg isotopes close to the drip line[†]

Kenichi Yoshida

[nuclear structure, density functional theory, unstable nuclei]

Presently, small excitation energies of the first 2^+ state and striking enhancements of $B(E2; 0_1^+ \rightarrow 2_1^+)$ in ^{32}Mg[1] and ^{34}Mg[2-4] are being actively discussed in connection with the onset of quadrupole deformation, breaking of the $N = 20$ spherical magic number, pairing correlation and continuum coupling effects. In order to get clear understanding of the nature of quadrupole deformation and pairing correlations, it is highly desirable to explore, both experimentally and theoretically, excitation spectra of these nuclei toward a drip line.

We apply the new calculation scheme of the deformed Quasiparticle-RPA on top of the Skyrme-Hartree-Fock-Bogoliubov mean field developed in Ref.[5] to the low-frequency excitation modes in neutron-rich Magnesium isotopes close to the drip line, and investigate the microscopic mechanism of the excitation modes uniquely appearing in deformed neutron-rich nuclei.

Figure 1 shows the low-lying excitation spectra for the $K^\pi = 0^+$ modes appearing as the 0_2^+ states. Here excitation energies are evaluated by

$$E(I, K) = \hbar\omega_{\rm RPA} + \frac{\hbar^2}{2\mathcal{J}_{\rm TV}}(I(I + 1) - K^2), \qquad (1)$$

in terms of the vibrational frequencies $\omega_{\rm RPA}$ and the Thouless-Valatin moment of inertia $\mathcal{J}_{\rm TV}$ calculated microscopically by the QRPA as described in Ref.[6]. As can be seen in this figure, the appearance of the soft $K^\pi = 0^+$ modes is quite sensitive to the neutron number, *i.e.*, the shell structure around the Fermi level of neutrons.

In Ref.[6], we have discussed the generic feature of the low-lying $K^\pi = 0^+$ modes in deformed neutron-rich nuclei using a phenomenological mean field and QRPA model: In a deformed system where the up-sloping oblate-type and the down-sloping prolate-type orbitals exist near the Fermi level, one obtains a low-lying mode possessing enhanced strengths both for the quadrupole p-h transition and for the quadrupole p-p (pair) transition induced by the pairing fluctuations. The up-sloping and down-sloping orbitals have quadrupole moments with opposite signs. In the present calculation employing the SkM* energy density functional, and the mixed-type pairing energy density functional, we obtain similar conclusions.
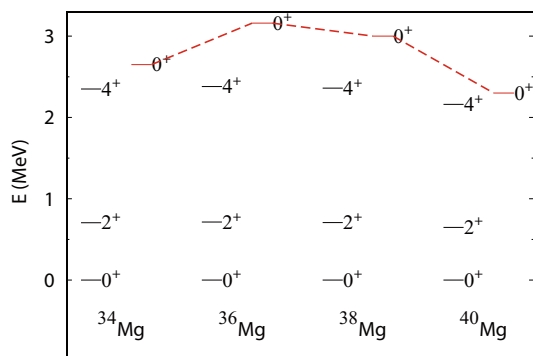
Furthermore, it is found that the low-lying collective modes in drip-line nuclei are characterized by the enhancement of excitation of neutrons. We summarize in Table 1 the ratio of the matrix elements for neutrons and protons normalized by that of the neutron and proton numbers, $(M_\nu/M_\pi)/(N/Z)$, for the lowest excitation modes. As the neutron drip line is approached, the contribution of the neutron excitation increases. This is understood as follows: In drip-line nuclei, the neutron two-quasiparticle (2qp) excitations predominantly take place outside of the nuclear surface. Therefore, the transition strengths of the 2qp excitation of neutrons become large. The proton p-h excitations, however, concentrate in the surface region. Consequently, coupling of the excitations between neutrons and protons becomes smaller, and the transition strengths of neutrons (M_ν^2) and protons (M_π^2) become extremely asymmetric.

Table 1. Ratios of the neutron and proton matrix elements M_ν/M_π divided by N/Z.

	^{34}Mg	^{36}Mg	^{38}Mg	^{40}Mg
$K^\pi = 0^+$	1.57	1.58	1.82	1.91
$K^\pi = 2^+$	1.41	1.41	1.55	1.79

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Fig. 1. Low-excitation energy spectra of ^{34,36,38,40}Mg.

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Evolution of the spin-orbit splitting in ^{48}Ca probed by the spectroscopic factor

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[Nuclear structure, shell model, unstable nuclei]

Evolution of the shell structure in unstable nuclei is attracting significant interest among radioactive beam facilities throughout the world. The disappearance of the $N = 20$ magic number and the appearance of a new $N = 16$ magic number were excellently described by shell-model calculations with the SDPF-M interaction,[1] where the changing magic structure is caused by a strong $T = 0$ monopole interaction between $0d_{3/2}$ and $0d_{5/2}$. Recently, it has been pointed out that this strong monopole interaction between the particular orbits is an example of the evolution of the shell structure (referred to as "shell evolution") caused by the tensor force.[2] The present study aims to investigate dominance of the tensor force in shell evolution based on a shell-model calculation including an appropriate tensor force. The work was carried out in part as a RIKEN-CNS collaboration project on large-scale nuclear structure calculations.

We constructed a new sd-pf shell interaction. Standard shell-model interactions were adopted as the intra-shell interactions: USD[3] for the sd shell and GXPF1B (a small modification to GXPF1A[4]) for the pf shell. We substituted a newly constructed interaction for the cross-shell part. Its tensor force is the $\pi + \rho$ exchange potential with cutoff at 0.7 fm,[2] and the central force is a single-range Gaussian force whose parameters are determined so as to give a monopole centroid similar to that of the GXPF1 interaction. Note that no direct fitting to experiment is adopted to determine the interaction.

While the central force is hardly responsible for the evolution of the spin-orbit splitting, the tensor force strongly reduces that of the proton as neutrons occupy the intruder orbit such as $0f_{7/2}$. We thus study the proton hole states in ^{47}K to examine the dominance of the tensor force in the shell evolution. Since proton $0d_{5/2}$ is located rather deeply there, its hole state does not concentrate on a single level but fragments into many levels. In such cases, the spectroscopic factor gives essential information on the single-particle (or

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Fig. 1. Comparison of the distribution of spectroscopic factors for one-proton pickup from ^{48}Ca between an (e, $e'p$) experiment[5] (upper) and the shell-model calculation (lower). Overall quenching by 0.7 is included in the calculation. The spectroscopic factors of $0d_{5/2}$ are presented by thick lines. Taken from[6].

hole) level. In Fig. 1, the distribution of spectroscopic factors for one-proton pickup from ^{48}Ca is compared between experiment and the present calculation. Both the position of the $5/2^+$ states and their spectroscopic factor strength are reproduced very well. If there is no tensor force in the cross-shell interaction, the spin-orbit splitting between proton d orbits becomes larger. Then, the agreement of the $0d_{5/2}$ hole states is significantly worse so that the two major peaks at around 3 MeV and 5 MeV are reduced and the peak of around 9 MeV is enhanced. Hence, this result provides a clear evidence for the significance of the tensor force in shell evolution.

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Density functional for description of novel pairing properties in nuclei far from β-stability

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[Neutron-rich nuclei, pairing correlations, density functional theory]

Aiming for a universal description of pairing correlations in nuclei far from β-stability, we extend the energy density functional (DF) by enriching the density dependence of the isoscalar and isovector couplings in the particle-particle channel (pair-DF). We emphasize the necessity of the quadratic isovector density term[1] in addition to the linear terms[2] for description of pairing properties in nuclei with large neutron excess.

We propose a pair-DF of the following form;

$$H_{\text{pair}}\left(\boldsymbol{r}\right) = \frac{V_0}{4} \sum_{\tau=n,p} g_\tau\left[\rho,\rho_1\right] \left\{\tilde{\rho}_\tau\left(\boldsymbol{r}\right)\right\}^2 \tag{1}$$

with

$$g_\tau\left[\rho,\rho_1\right] = 1 - \frac{1}{2}\frac{\rho\left(\boldsymbol{r}\right)}{\rho_0} - \eta_1\frac{\tau_3\rho_1\left(\boldsymbol{r}\right)}{\rho_0} - \eta_2\left(\frac{\rho_1\left(\boldsymbol{r}\right)}{\rho_0}\right)^2 \tag{2}$$

Here $\tau = n$ (neutron) or p (proton), the strength V_0, and $\rho_0 = 0.16$ fm^{-3} is the saturation density of symmetric nuclear matter. ρ (ρ_1) is isoscalar (isovector) density. The $\tau_3 = 1$ (n) or -1 (p) in the linear ρ_1 term is introduced so as to preserves the charge symmetry of the pair-DF.

The parameters η_1 and η_2 are optimized so as to reproduce the average dependence of pairing gaps on the mass number A and asymmetry parameter $\alpha = (N - Z)/A$:

$$\Delta_{n,\exp}\left(\alpha\right) = \left(1 - 7.74\,\alpha^2\right)\Delta_n^{(A)} \tag{3}$$

$$\Delta_{p,\exp}\left(\alpha\right) = \left(1 - 8.25\,\alpha^2\right)\Delta_p^{(A)}, \tag{4}$$

with $\Delta_n^{(A)} = 6.75/A^{1/3}$ MeV and $\Delta_p^{(A)} = 6.36/A^{1/3}$ MeV[1]. For this purpose, we performed the extensive Hartree-Fock-Bogoliubov (HFB) calculation with Skyrme SLy4 force for 156 even-even nuclei around the region of $A = 120 - 120$ and $\alpha = 0.05 - 0.25$. We showed that the parameters set $(\eta_1, \eta_2) = (0.2, 2.5)$ not only gives a good description of the A- and α- dependence[1] (see Fig. 1, for neutron pairing gaps Δ_n), but also minimamizes the r.m.s. deviation between the measured and calculated pairing gaps (Fig. 2). The r.m.s deviation is defined by

$$\sigma_{tot} = \left[\frac{1}{N_{\exp}} \sum_\tau \sum_{N,Z} \left(\Delta_{\tau,\text{HFB}} - \Delta_{\tau,\exp}\right)^2\right]^{1/2} \tag{5}$$

Here $N_{\exp} = 177$ is the number of existing data for pairing gaps in the region of the present investigation.

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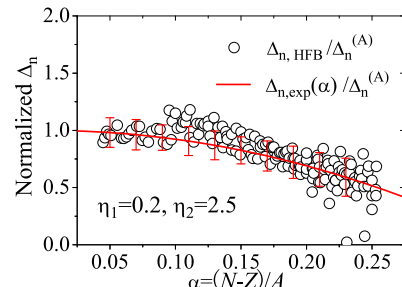
Fig. 1. Neutron pairing gaps obtained with $(\eta_1, \eta_2) = (0.2, 2.5)$ are plotted as a function of α. The pairing gaps are divided by $\Delta_n^{(A)}$. The V_0 is fixed so as to reproduce the measured Δ_n of ^{156}Dy.
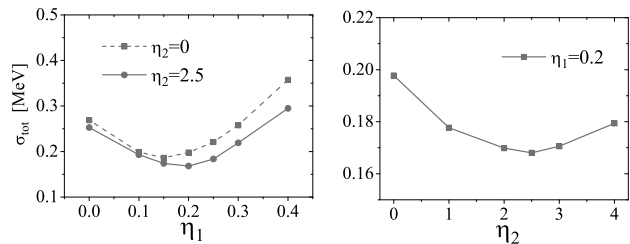
Fig. 2. (Left) The r.m.s. deviations are shown as a function of η_1. The results with either $\eta_2 = 0$ or $5/2$ are compared. (Right) The same but as a function of η_2 with $\eta_1 = 0.2$. The V_0 is fixed for each (η_1, η_2) so as to reproduce the measured Δ_n of ^{156}Dy.

The strength V_0 is fixed so as to reproduce the mesured Δ_n of ^{156}Dy. This enables us to reduce the computational efforts considerably compared to the determination of V_0 by χ^2 fitting to the experimental data in the wide region of the nuclear chart. This choice gives $\sigma_{tot} = 0.17$ MeV, which is close to $\sigma_{tot} = 0.16$ MeV obtained with the optimized V_0, and much smaller than $\sigma_{tot} = 0.34$ MeV with the standard choice reproducing the measured Δ_n of ^{120}Sn.

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Two-neutron and two-proton correlations in nuclear surface

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[NUCLEAR STRUCTURE, Unstable nuclei, Cluster]

Two-neutron correlation in neutron-rich nuclei is presently one of the hot subjects in the physics of unstable nuclei. In two-neutron halo nuclei such as ^{11}Li, the dineutron correlation was theoretically predicted in many works and was supported by experiments. The dineutron correlation, which is characterized by a strong spatial correlation of two neutrons in the ^1S channel, is discussed also in light neutron-rich nuclei such as ^{8}He[1-3] and also in medium-heavy neutron-rich nuclei[4,5] as well as asymmetric nuclear matter[6,7].

Our aim in this paper is to reveal how two neutrons can form in the nuclear surface. For this aim, we consider a very simplified model of quasi two-dimensional(2D) neutron systems which mimic a neutron layer in the surface where distribution of valence neutrons concentrates. We assume for simplicity that the transverse z-direction of the quasi-2D plane can be approximated by a frozen Gaussian packet,

$$\phi^{0s}(z) = \left(\frac{1}{\pi a^2}\right)^{1/4} \exp\left[-\frac{z^2}{2a^2}\right], \tag{1}$$

whereas the motion of the neutrons within the layer is free. Let us consider an two-neutron system in this quasi-2D space. By integrating the z coordinates, we can get the 2D Schrödinger equation with respect to $r_\perp \equiv \sqrt{x^2 + y^2}$ for the S-wave relative wave function $\Phi^{nn}(r_\perp, \chi_1, \chi_2)$,

$$\left(-\frac{\hbar^2}{m}\left(\frac{\partial^2}{\partial r_\perp} + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\right) + V^{2D}(r_\perp)\right)\Phi^{nn}(r_\perp, \chi_1, \chi_2)$$
$$= E_{nn}^{2D}\Phi^{nn}(r_\perp, \chi_1, \chi_2), \tag{2}$$
$$\Phi^{nn} = \psi^{nn}(r_\perp) \otimes X_{S=0}(\chi_1, \chi_2), \tag{3}$$
$$V^{2D}(r_\perp) = \langle \phi^{0s}(z_1)\phi^{0s}(z_2)| V(r) |\phi^{0s}(z_1)\phi^{0s}(z_2)\rangle. \tag{4}$$

$\psi^{nn}(r_\perp)$ is the spatial wave function normalized as $\int d^2 r_\perp |\psi^{nn}(r_\perp)|^2 = 1$, and $X_{S=0}$ is the intrinsic-spin wave function for the spin-zero channel.

We calculated the two-neutron wave function in quasi-2D with the width a by using the Minnesota force which is an effective interaction adjusted to the experimental S-wave NN scattering lengths. It is known that a bound state in 2D can form at any arbitrarily small attraction. Since the ^1S nuclear force is attractive at low energy, the two-neutron bound state is formed in quasi-2D with an arbitrary width a. Because the interaction $V^{2D}(r_\perp)$ in 2D space becomes stronger for the smaller width a of the layer than the larger

one, energy and size of the two-neutron bound state decrease as the width a gets small. For example, in quasi-2D with $a = 1$, the energy E_{nn}^{2D} is -1.9 MeV and the size $\langle r_\perp^2 \rangle = 4.3$ fm. In Fig. 1, the calculated wave functions of the two-neutron and the two-proton states in quasi-2D are shown. The wave function $\psi^{nn}(r_\perp)$ shows the prominent peak at small distance $r_\perp$ region in quasi-2D with $a = 1$ and $a = 2$ fm. This indicates that the spatial correlation of two neutrons is enhanced in quasi-2D systems. We also calculated the wave function for an two-proton system in quasi-2D by adding the Coulomb force, and found that the two-proton correlation is still prominent if the layer is thin enough as $a = 1 - 2$ fm.

The present results suggest that, if valence neutrons (protons) concentrate in the surface layer of neutron-rich (proton-rich) nuclei, spatial correlations of two neutrons (protons) in $S = 0$ channel can be enhanced.
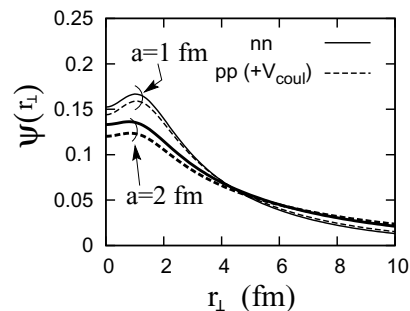
Fig. 1. Two-neutron and two-proton wave functions $\psi^{nn}(r_\perp)$ $\psi^{pp}(r_\perp)$ in quasi-2D with the width parameter $a = 1$ and $a = 2$ fm calculated with the Minnesota force with and without the Coulomb force.

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Calculation of nuclear photoabsorption cross section using the finite amplitude method for Skyrme functionals

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[Nuclear structure, random-phase approximation, photonuclear reaction]

In the description of the dynamical properties in the nuclear response to external fields, the random-phase approximation (RPA) is a leading theory applicable to both low-lying states and giant resonances. The RPA is a microscopic theory, which can be obtained by linearizing the time-dependent Hartree-Fock (TDHF) equation, or equivalently, the time-dependent Kohn-Sham equation in density-functional theory. The linearization produces a self-consistent residual interaction, $v = \delta^2 E[\rho]/\delta\rho^2$, where E and ρ are the energy-density functional and the one-body density, respectively. The standard solution of the RPA is based on the matrix formulation of the RPA equation, which involves a large number of particle-hole matrix elements of the residual interaction, $v_{ph',hp'}$ and $v_{pp',hh'}$. Since the realistic nuclear energy functional is rather complicate, it is a hard work to calculate all the necessary matrix elements. Although there have been numerous studies on HF-plus-RPA calculations, because of this complexity it has been a common practice to neglect some parts of the residual interactions. RPA calculations with the full self-consistency are becoming a current trend in nuclear structure studies, however, the applications to deformed nuclei are still scarce.

Recently, we have proposed a new practical method of solving the RPA equation, which we name the finite amplitude method (FAM)[1]. The most advantageous feature of the present approach is that it does not require an explicit calculation of the residual interactions. Instead, the FAM estimates them using the operations of the single-particle Hamiltonian with the numerical differentiation. The numerical procedure is as follows. First, we calculate the ground state using the imaginary-time method, and obtain the single-particle orbitals and their eigenenergies:

$$h_0|\phi_i\rangle = \epsilon_i|\phi_i\rangle. \tag{1}$$

Then, we solve the following linear response equations by iteration.

$$\omega|X_i\rangle = (h_0 - \epsilon_i)|X_i\rangle + \hat{P}\{V_{ext} + \delta h\}|\phi_i\rangle, \tag{2}$$

$$-\omega\langle Y_i| = \langle Y_i|(h_0 - \epsilon_i) + \langle\phi_i|\{V_{ext} + \delta h\}\hat{P}. \tag{3}$$

Here, V_{ext} indicates an external perturbative field, and $\hat{P}$ the projection operator onto the particle space. $|X_i\rangle$ and $|Y_i\rangle$ are RPA forward and backward amplitudes, respectively, δh is the induced residual field, which is

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evaluated with the FAM technique[1].

Figure 1 shows the accuracy of the FAM. Smearing the result of the diagonalization of the RPA matrix (vertical lines)[2] with a width of 2 MeV, we obtain the solid curve. Circles indicate the results of the FAM. These two different calculations provide identical results. This proves that the numerical differentiation in the FAM for realistic Skyrme functionals is sufficiently accurate in practice. Note that the required computational resource for the diagonalization method is much larger than that for the FAM. As an example of the FAM results, we show in Fig. 2 the calculated photoabsorption cross sections for deformed ^{24}Mg and ^{28}Si. The systematic calculations of nuclear photoabsorption cross sections are under progress.

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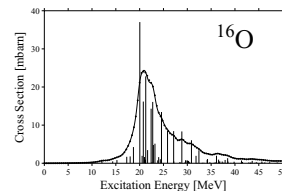
Fig. 1. Comparison of the photoabsorption cross sections for ^{16}O obtained with different methods. The SIII parameter set is used. See text for explanation.
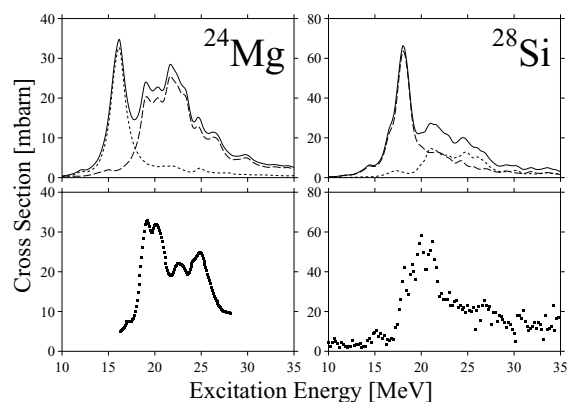
Fig. 2. Calculated photoabsorption cross sections in light deformed nuclei ^{24}Mg and ^{28}Si with experimental data.

Linear Response Calculations With Skyrme TDHF+BCS

S. Ebata,*1 T. Nakatsukasa T. Inakura,*1,*2 Y. Hashimoto,*2 and K. Yabana*1,*2

[Nuclear structure, unstable nuclei]

The recent progress of radioactive facilities, such as RIBF in RIKEN, strongly demands a theoretical framework that is able to analyze and predict the properties of unknown nuclei. For this purpose, it should include the effects of deformation and pairing correlation, and should be capable of calculating not only the ground state but also the excited states. The Hartree-Fock-Bogoliubov plus quasi-particle random phase approximation (HFB+QRPA) is such a candidate, which is applicable to a wide range of nuclei from light to heavy ones. However, it requires a lot of effort for coding the programs as well as significant computational resources. The HFB+QRPA for deformed nuclei is currently still in preliminary stage.

We propose the time-dependent Hartree-Fock plus BCS (TDHF+BCS) in the three-dimensional coordinate-space representation, which can take into account the full effects of nuclear deformation, yet treating the pairing correlation in the BCS-like approximation.

TDHF+BCS equations are derived from the time-dependent variational principle[1]. First, we set a time-dependent trial wave function as a BCS-like state

$$|\Phi(t)\rangle \equiv \prod_{l>0}(u_l(t) + v_l(t)\hat{c}_l^\dagger(t)\hat{c}_{\bar{l}}^\dagger(t))|0\rangle.$$

Here, $\hat{c}_l^\dagger$ and $\hat{c}_{\bar{l}}^\dagger$ are creation operators of canonical states. Note that the state $\bar{l}$ is not necessarily the time-reversal state of the state l. Differentiating the Lagrangian, $\mathcal{L}(t) = \langle\Phi(t)|\ \hat{H} - i\hbar\partial/\partial t\ |\Phi(t)\rangle$, with respect to the single-particle states ϕ_l, ϕ_l^* and the occupation probability parameters v_l, v_l^*, we can derive the following equations for the single-particle states $\phi_l(\mathbf{r},t)$, the occupation probabilities $\rho_l \equiv |v_l|^2$, and the pair densities $K_l \equiv u_l v_l$:

$$\begin{cases} i\hbar\dot{\phi}_l(\mathbf{r},t) = \left(\hat{h}[\rho,\tau] - \varepsilon_l\right)\phi_l(\mathbf{r},t), \\ i\hbar\dot{\rho}_l(t) = \Delta^* K_l(t) - \Delta K_l^*(t), \\ i\hbar\dot{K}_l(t) = K_l(t)(\varepsilon_l + \varepsilon_{\bar{l}}) + \Delta(2\rho_l(t) - 1), \end{cases}$$

where we used the normalization condition, $u_l^2 + |v_l|^2 \equiv 1$. $\Delta \equiv G\sum_{l>0}K_l$ is the gap energy, the constant G is the strength of pairing interaction, and ε_l are the single-particle energies. The TDHF+BCS equations guarantee the conservation of the orthonormal property of single-particle states, the particle number, and the total energy. In the static limit, these equations agree with the well-known HF+BCS equations. With $\Delta = 0$, these are also equivalent to the TDHF equation.

We solve the TDHF+BCS equations in real time, and calculate the liner response of nuclei. In the liner-response calculation, we add an external field $\hat{V}_{\text{ext}}(\mathbf{r},t)$ which is weak and instantaneous in time, $\hat{V}_{\text{ext}}(\mathbf{r},t) \equiv -k\hat{F}\delta(t);\ k \ll 1$. $\hat{F}$ is a one-body operator, for example, the isovector dipole operator, $\hat{D}_{\text{IV}} = (N/A)\sum_p \hat{z}_p - (Z/A)\sum_n \hat{z}_n$. We calculate the time evolution of the expectation value of $\hat{F}$, and obtain the strength function $S(\hat{F};E)$ by using the Fourier transformation.

$$S(\hat{F};E) = -\frac{1}{k\pi}\text{Im}\int_0^\infty dt\,(f(t) - f(0))\,e^{iEt - \Gamma t/2},$$

$$f(t) \equiv \langle\Phi(t)|\ \hat{F}\ |\Phi(t)\rangle,$$

where Γ is a smoothing parameter.

Figure 1 shows the $E1$ strength function for ^{24}Ne, calculated with the SkM* parameter set. In this calculation, the ground state of ^{24}Ne is deformed to an oblate shape. The ground-state deformation is slightly smaller than that in the HF state without the pairing correlation. The strength function calculated with the TDHF+BCS turns out to be similar to that with the TDHF. For this nucleus, we have found that the effects of pairing correlation is weak for giant dipole resonance.

Currently, we are developing the TDHF+BCS code for parallel computing to facilitate the calculation of heavier nuclei. Following on from that, we will perform a systematic investigation of nuclear responses.
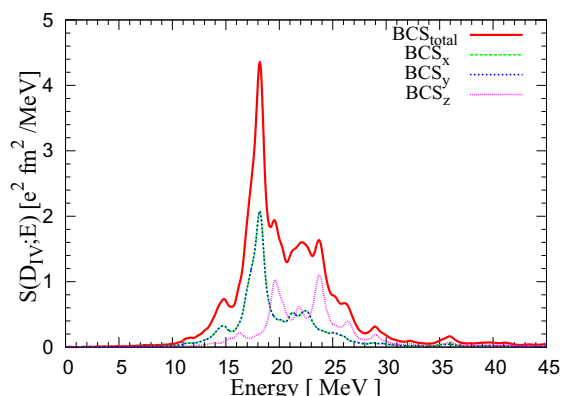
Fig. 1. The $E1$ strength function for ^{24}Ne calculated with the Skyrme functional of the SkM* parameter set. The smoothing parameter of $\Gamma = 1$ MeV is used.

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Development of QRPA code with an FAM method

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[Nuclear structure, QRPA]

QRPA is a technique successfully employed to study the low-lying excited states and giant resonances of a nucleus where pairing correlations cannot be neglected. The idea behind this study is to generalize the Finite Amplitude Method (FAM) for random phase approximation (RPA)[1] to quasi particle RPA (QRPA). QRPA can be obtained as a limit for small amplitude oscillations from the Time Dependent Hartree Fock Bogoliubov equations (TDHFB)[2]

$$i\hbar\frac{\partial \mathcal{R}}{\partial t} = [\mathcal{H}(t) + F(t), \mathcal{R}(t)] \tag{1}$$

where $\mathcal{R}(t)$ is the generalized density matrix, $\mathcal{F}(t)$ is the external perturbation field, which may include two particle transfer operators, and $\mathcal{H}(t)$ is the HFB Hamiltonian:

$$\mathcal{H} = \begin{pmatrix} h & \Delta \\ \Delta^\dagger & -h \end{pmatrix}$$

In the frequency representation for small amplitude oscillations Eq. (1) becomes

$$\hbar\omega\mathcal{R}' = [\mathcal{H}', \mathcal{R}^0] + [\mathcal{H}^0, \mathcal{R}'] + [\mathcal{F}, \mathcal{R}^0] \tag{2}$$

Where

$$\mathcal{R}(t) = \mathcal{R}^0 + \mathcal{R}' e^{i\omega t} + h.c. \tag{3}$$

$$\mathcal{H}(t) = \mathcal{H}^0 + \mathcal{H}' e^{i\omega t} + h.c. \tag{4}$$

and the generalized density is:

$$\mathcal{R}' = \begin{pmatrix} \rho' & k' \\ \bar{k}' & -\rho' \end{pmatrix}$$

These equations not only involve the diagonalization of large matrices, but also calculation of the matrix elements is generally very difficult. In the past, analytic calculation of the self-consistent residual interaction has been truncated, so the results were not completely self-consistent. The variation of the HFB Hamiltonian is

$$\mathcal{H}' = \begin{pmatrix} \mathcal{H}'^{11} & \mathcal{H}'^{12} \\ \mathcal{H}'^{21} & \mathcal{H}'^{22} \end{pmatrix}$$

Calculation of the matrix $\mathcal{H}'$ involves the evaluation of:

$$\frac{\partial^2 \mathcal{E}}{\partial\rho_{kl}\partial\rho_{ij}^*}\rho_{kl}'; \quad \frac{\partial^2 \mathcal{E}}{\partial k_{kl}\partial\rho_{ij}^*}k_{kl}'; \quad \frac{\partial^2 \mathcal{E}}{\partial\bar{k}_{kl}\partial\rho_{ij}^*}\bar{k}_{kl}' \tag{5}$$

where the derivatives are evaluated on the HFB ground state.

In the HF+RPA ($\Delta = 0$), the FAM provides a feasible evaluation of δh by taking a numerical derivation (η being a small parameter)[1]

$$\delta h(\omega) = \frac{1}{\eta}(h[\langle\psi'|, |\psi\rangle] - h[\langle\phi|, |\phi\rangle]) \tag{6}$$

which is correct with a proper choice of $\langle\psi'|$ and $|\psi\rangle$ as combinations of the single-particle orbitals and the forward- and backward-going amplitudes. This numerical derivation allows to obtain the RPA equations from a Hartree-Fock code with simple modifications. The RPA equations are then solved by using iterative methods. In QRPA, there is the second derivative of the energy respect not only to the normal density, but also the abnormal density. Currently we are developing a framework for the FAM, which can be applied to HFB+QRPA.

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Spectroscopic Factors in Asymmetric Nuclei From Realistic Interactions

C. Barbieri,[*]

Spectroscopic factors (SFs) for particle and hole states around closed shell nuclei are of particular interest since they carry important information regarding nuclear structure.[1,2] Strong deviations from unity signal the onset of substantial correlation effects and imply the existence of non trivial many-body dynamics. Understanding how SFs change when moving close to the drip lines is important to constrain theoretical models for studying radioactive isotopes. The first information on these features has recently become available using one-nucleon knockout experiments in inverse kinematics. In general, it is found that SFs do change with proton-neutron asymmetry and the quenching of quasiparticle orbits (and hence correlations) become stronger with increasing separation energy.[3]

Spectroscopic factors for both symmetric and asymmetric nuclei are being calculated within the framework of self-consistent Green's functions theory. Calculations are large scale and based on modern realistic nuclear forces. The Faddeev random phase approximation (FRPA) method is used to account for the interaction between nucleons and collective excitation of the nucleus.[4,5] This is done by resumming Feynman diagrams such as the one depicted in Fig. 1. There, the $\Pi(\omega)$ and $g^{II}(\omega)$ propagators carry information on the collective motion of particle-hole (giant resonance) and two-particle or two-hole (pairing like) configurations. The effects of short-range correlations are also taken into account by using the G-matrix technique.
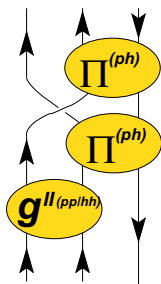
Fig. 1. Example of a diagram appearing in the all-orders summation generated by the FRPA method.

Figure 2 shows the first FRPA results for the spectroscopic factors of quasiparticles around ^{16,28}O and ^{40,60}Ca.[6] These are based on the realistic chiral N3LO interaction.[7] A dependence on proton-neutron asymmetry is indeed observed in the FRPA, with the spectroscopic factors becoming smaller with increasing nu-

cleon separation energy. A dispersive optical model analysis, which is constrained to data up to ^{48}Ca, has also been extrapolated to proton rich Ca isotopes, with similar findings.[8,9] However, for both analyses the change in magnitude is significantly smaller than the one deduced from direct knockout data.[3]
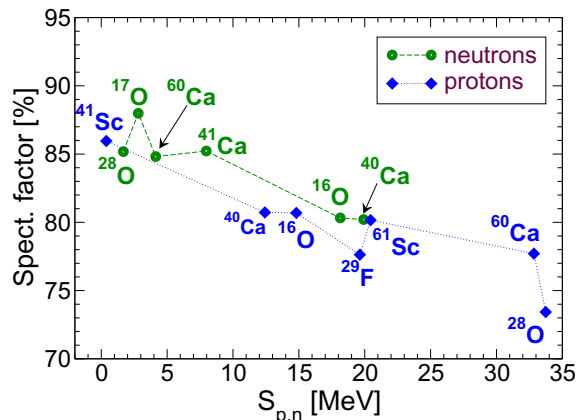
Fig. 2. SFs obtained from partially self-consistent FRPA. All numbers are given as a fraction of the IPM value and refer to transitions from ground state to ground state. The points refer to knockout of a nucleon from the isotope indicated nearby. The lines are a guide to the eye.

Collective excitations, from Fig. 1 are the most important degrees of freedom governing the reduction of SFs.[6] These are properly accounted for by the FRPA approach. However, realistic two-nucleon forces such as the one used here have a tendency to underestimate their importance. Hence, the dependence on asymmetry seen in Fig. 2 may become more substantial once FRPA calculations with improved forces are available.

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Ab-initio Green's Functions Calculations of Atoms

C. Barbieri,[*1] and D. Van Neck[*2]

Density functional theory (DFT) allows for acurate calculations of ground states energies, while only single-particle (sp) equations must be solved. There is therefore a continuing interest in studying conceptual improvements and extensions to the DFT framework. An approach in this direction has been proposed in Ref.[1] by developing a quasi-particle (QP)-DFT formalism, in which QP properties can be obtained along with ground state energies. Given the close relation between QP-DFT and the Green's functions (GF) formulation of many-body theory, we employ *ab initio* calculations in the latter formalism to investigate the structure of possible QP-DFT functionals. Recent advances in such calculations are reported below.

We employ the Faddeev random phase approximation (FRPA) expansion of the self-energy[2,3]. This method explicitly accounts for coupling of electrons to particle-hole (ph) and two-particle (pp) or two-hole (hh) collective excitations of the system. The latter are obtained in the RPA framework. The FRPA method includes the GW approximation but goes further beyond since it accounts completely for exchange correlations at the 2p1h/2h1p level and it includes the propagation of pp/hh configurations.

	Hartree-Fock	FRPA	Exp.[5,6]
He	-2.860 (+44)	-2.903 (+1)	-2.904
Be	-14.573 (+94)	-14.643 (+24)	-14.667
Ne	-128.547 (+281)	-128.917 (+11)	-128.928
Mg	-199.617 (+426)	-200.058 (-15)	-200.043

Table 1. Hartree-Fock and Faddeev-RPA binding energies (in Hartree) extrapolated from the cc-pVTZ and cc-pVQZ basis sets. The deviations from the experiment are indicated in parentheses (in mH). For Mg, the cc-pCV(TQ)Z bases were used.

Calculations were performed in the correlation consistent cc-pVTZ and cc-pVQZ gaussian bases for all atoms except for the ground state energies of Mg, for which the core-valence version cc-pCV(TQ)Z was used[4]. The results were then extrapolated to the basis set limit according to $E_X = E_\infty + AX^{-3}$. Table 1 shows the results for the FRPA ground state energies and compares them to the experiment and the corresponding Hartree-Fock results. FRPA gives practically exact results for the two electron problem (He) and accounts for 96% of the correlation energy in the larger atoms. The atom of Be is an exception due to the pres-

		Hartree-Fock	FRPA	Exp.[5,6]
He:	1s	0.918 (+14)	0.900 (-4)	0.904
Be:	2s	0.309 (-34)	0.322 (-21)	0.343
	1s	4.733 (+200)	4.540 (+7)	4.533
Ne:	2p	0.850 (+57)	0.803 (+10)	0.793
	1s	1.931 (+149)	1.795 (+13)	1.782
Mg:	3s	0.253 (-28)	0.277 (-4)	0.281
	2p	2.281 (+161)	2.130 (+10)	2.12
Ar:	3p	0.590 (+11)	0.578 (-1)	0.579
	3s	1.276 (+201)	1.065 (-10)	1.075
	2p	9.570 (+410)	9.199 (+39)	9.160

Table 2. Ionization energies obtained from Hartree-Fock and the Faddeev-RPA method (in Hartree). All results are extrapolated from the cc-pVTZ and cc-pVQZ bases. The deviations from the experiment are given in mH.

ence of very soft excitations in the $J^\pi=1^-$,S=1 channel which can drive the ph RPA equation to instability.

Ionization energies are shown in Tab. 2. The extrapolated results deviate from experiment by about 5 mH for the first ionization energies, while it increases to 10-15 mH for the separation of slightly deeper electron orbits. Schirmer and co-workers already pointed out the importance of a treatment that is consistent with at least third order perturbation theory[7]. The present formulation of the FRPA fully includes of such correlations. At the same time, the explicit inclusion of RPA phonons holds the promise for successful applications to extended systems. Further work will be required to verify that this is indeed the case.

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Thermodynamical ensemble treatments of nuclear pairing in a multilevel model

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[NUCLEAR STRUCTURE, thermodynamic ensembles, superfluid-normal phase transition, thermal fluctuations, selfconsistent quasiparticle RPA, exact solution of pairing problem.]

The thermodynamic properties of infinite systems, such as superfluidity or superfluid-normal (SN) phase transition, are usually described by three principal ensembles, namely the grand canonical ensemble (GCE), canonical ensemble (CE) and micro canonical ensemble (MCE). The GCE consists of identically systems in thermal equilibrium, each of which shares its energy and particle number with an external heat bath. The CE is also in contact with the heat bath, but the particle number is fixed, whereas the MCE is an ensemble of thermally isolated system sharing the same energy and particle number. In thermodynamic limit, fluctuations of energy and particle number are zero, therefore three types of ensembles offer the same average values for thermodynamic quantities. However, the discrepancies between the predictions by these ensembles arise when thermodynamics is applied to small systems such as atomic nuclei or nanometer-size clusters.

In the present work, we carry out a systematic comparison of predictions for nuclear pairing properties obtained by averaging the exact solutions of the pairing problem[1] in three principal thermodynamic ensembles as well as those offered by recent microscopic approaches to thermal pairing. For the latter, we choose the unprojected and particle-number projected versions of the FTBCS1+SCQRPA, which we recently developed in Ref.[2].

The numerical calculations are performed for the pairing gap, total energy, heat capacity, entropy, and microcanonical temperature within the doubly-folded equidistant multilevel pairing model. The results obtained show that the sharp SN phase transition, which is predicted by the conventional finite-temperature BCS (FTBCS) theory, is smoothed out in exact calculations within all three principal ensembles. The results obtained within the GCE and CE are very close to each other even for systems with small number of particles. As for the MCE, although it can be used to study the pairing properties of isolated systems at high excitation energies, there is a certain ambiguity in the temperature extracted from level density due to the discreteness of a small-size system. This ambiguity depends on the shape and parameter of the distribution employed to smooth the discrete level density. We found that, in this respect, the Gaussian distribution gives the best fit for both of the temperature and entropy to the canonical values. The predictions by

Fig. 1. Pairing gaps Δ, total energies $\langle \mathcal{E} \rangle$, and heat capacities C as functions of temperature T, obtained within a doubly-folded equidistant multilevel pairing model for $N = 8$, 10, and 12 particles and pairing interaction parameter $G = 0.9$ MeV. The dotted, thin dashed, thick dashed, thin dash-dotted and thick dash-dotted lines denote the FTBCS, FTBCS1+SCQRPA, FTLN1+SCQRPA, CE, and GCE results, respectively. The thin solid line shows the pairing gap obtained from the simple extension of the odd-even mass formula to $T \neq 0$, whereas the thick solid line represents the improved one.

the FTBCS1+SCQRPA and FTLN1+SCQRPA (i.e. FTBCS1+SCQRPA with Lipkin-Nogami's particle-number projection) are found in reasonable agreement with the GCE and CE results. The best agreement is seen between the FTLN1+SCQRPA and the GCE ones (See Fig. 1). We also suggest a novel formula to extract the pairing gap at finite temperature from the difference of total energies of even and odd systems, where the contribution of uncorrelated single-particle motion is subtracted. The new formula predicts a pairing gap in much better agreement with the canonical gap than the simple finite-temperature extension of the odd-even mass formula [See Figs. 1 (a1), (a2) and (a3)].

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BCS-BEC transition in finite systems

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[NUCLEAR STRUCTURE, pairing, superfluid-normal phase transition, BCS theory, quasi-particle RPA, BCS-BEC transition]

Superfluidity and superconductivity in infinite systems are well described by the Bardeen-Cooper-Schrieffer (BCS) theory, which is a mean-field approach that shows the occurrence of pairing correlations forming the condensate. The collapse of the BCS pairing gap at a critical temperature T_c^{BCS} signals the transition from the superfluid phase to the normal one. In the normal state the mean-field theory cannot describe two-body correlations. Nozières and Schmitt-Rink (NSR)[1] made an attempt to incorporate the effect of correlations on T_c in the electron-hole systems. In the weak coupling limit, the authors found the ordinary T_c^{BCS}. In the strong coupling limit, they found that the system is characterized by the non-interacting boson bound states that can undergo a Bose-Einstein condensation (BEC) at a specific critical temperature. NSR demonstrated a smooth transition from the strong to weak coupling limit (BCS-BEC transition).

However, NSR neglected the effect of the mean field created by the pairs. This effect is included in our selfconsistent quasiparticle random-phase approximation (SCQRPA)[2], which constitutes a fully selfconsistent extension of the NSR approach. The present study searches for the BCS-BEC transition in finite systems by using an exactly solvable doubly folded multilevel pairing model, for which the SCQRPA has been applied with success to describe the pairing correlations beyond the mean field. The model consists of Ω equidistant levels with energies $\epsilon_k = $ k-1 (MeV) ($k = 1, \ldots, \Omega$), i.e. positive except for the bottom of the spectrum with $\epsilon_1 = 0$. These levels interact via a constant attractive pairing force. If the interaction is sufficiently strong, two fermions form a singlet bound pair, whose minimum energy is $-\epsilon_1$ with ϵ_1 being the binding energy. The internal wave function ϕ_k of the pair creation extends over a characteristic distance $a_0 \sim \epsilon_1^{-1/2}$. If two bound pairs have only a small overlap ($|\phi_k| \ll 1$), they can be treated as a gas of structureless bosons. When this happens, the BCS equation reduces, in leading order, to the Schrödinger equation for a single bound pair, whose eigenvalue is the pair chemical potential $\mu_P \equiv 2\lambda$. Its zeroth order yields $2\lambda = \epsilon_1$, as for an ideal Bose gas. This means that μ_P reaches the bottom of the single-particle spectrum. As ϵ_1 is chosen to be zero, this means λ vanishes. We found that, for a half-filled ($N = \Omega$) or underfilled system ($N < \Omega$) at zero tem-
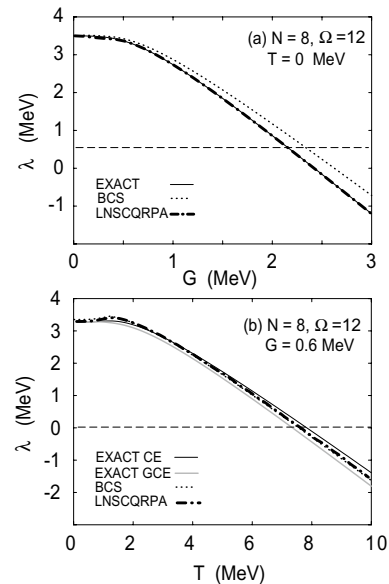
Fig. 1. Chemical potential λ for $N = 8$ and $\Omega = 12$ as a function of G at zero temperature T (a), and as a function of T at $G = 0.6$ MeV (b) as predicted by the exact canonical and grand-canonical calculations as well as the BCS and LNSCQRPA theories.

perature ($T = 0$), λ reaches zero at a certain value $G = G_c$ (Fig. 1), higher than which it turns negative and continues to decrease with increasing G. We also found that at $G < G_c$, the chemical potential λ decreases with increasing T, and eventually crosses zero at $T = T_c >> T_c^{BCS}$. The fact that the predictions by the SCQRPA with particle-number projection within the Lipkin-Nogami (LN) method (the LNSCQRPA) agree very well with the exact results up to a moderate temperature T shows that the SCQRPA is indeed a promising approach to study the BCS-BEC transition in finite systems. Several calculations to check if a finite system of pair fermions reaches that of bosons in the BEC limit within the SCQRPA at $T \neq 0$ are now underway. Tests in realistic neutron-rich nuclei are being carried out as well.

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t-band and tilted axis rotation in ^{182}Os

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We have proposed that there is a case where the *s*-band states become unstable against the tilting of a rotational axis in ^{182}Os[1]. We carried out intensive tilting calculations and found the so-called tilted axis rotational (TAR) states[2] which are stable against the tilting of a rotational axis for each angular momentum state from $J = 16\hbar$ to $30\hbar$ in ^{182}Os. Each of the TAR states seems to form a band which has nearly constant $K \sim 7.5$. This new band has lower energy than the *s*-band and appears as an yrast beyond $J = 18\hbar$[3]. We expect this portion of new band structure may support Walker's long-standing prediction that the *t*-band is responsible for the occurrence of backbending in the $A \sim 180$ region[4]. In this article, we report some of our results on the band structure consisting of the TAR states.

The tilt angle ψ is measured from the x-axis and is perpendicular to the symmetry axis(z-axis) along the prime meridian. The wave function $|\Phi(\psi)\rangle$ with tilt angle ψ is obtained by solving the 3D-CHFB equation with the pairing plus quadrupole Hamiltonian[2].

In Fig. 1, we plot the energies of the *s*-branches[1] for several angular momentum states. The shapes of the *s*-branches vary smoothly for all tilt angles ψ from 0° to 90° as the angular momentum value is increased. Each curve has a minimum point (TAR state) and their positions shift gradually toward the smaller tilt angle region as the angular momentum increases.

The approximate K quantum number of each TAR state is estimated by calculating the projection of the angular momentum along the z-axis at the minimum point. In Table 1, we show the projections $J\sin(\psi)$ of the angular momenta J from $18\hbar$ to $30\hbar$ which are shown in Fig. 1. Since the values of the projections are almost constant, it is expected that the family of the states at the minimum points of the *s*-branches form a band (TAR band).

We are now looking for the rest part of the band including a band head state ($J = 8\hbar$) which must exist in the region just above the *g*-band below the $J = 18\hbar$ band crossing point. This will require some more elaborate calculation techniques.

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Table 1. Projection of angular momentum along z-axis at minimum points on the *s*-branches in Fig. 1

J	tilt angle ψ	$J\sin(\psi)$
18	24°	7.3
22	20°	7.3
24	18°	7.6
26	17°	7.6
28	16°	7.7
30	15°	7.8
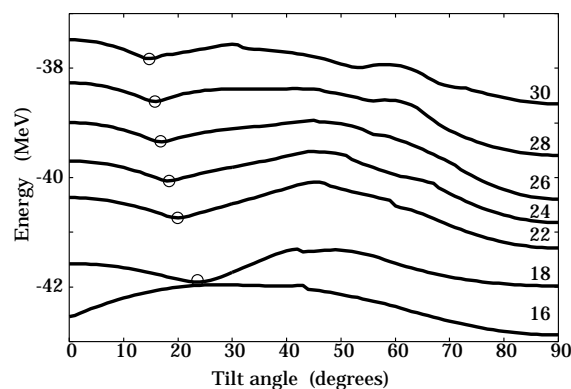
Fig. 1. Plot of energies of *s*-branches. Figures indicate the angular momentum J. Circles indicate minimum points of each curve.
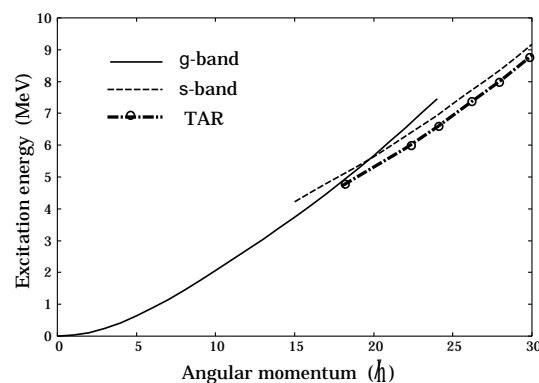
Fig. 2. Plot of energies of minimum points on *s*-branches in Fig. 1 (dash-dotted curve with circles labelled "TAR"). Circles on dash-dotted curve correspond to the position of minimum points labelled with circles in Fig. 1.

Origin of the narrow, single peak in the fission-fragment mass distribution for ^{258}Fm[†]

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[Nuclear reaction, fission, Macroscopic-Microscopic model]

In spontaneous fission of Fm isotopes, the fragment mass distributions change abruptly from a double-peaked, broad, mass-asymmetric distribution for ^{256}Fm to a single-peaked, very narrow, symmetric distribution for ^{258}Fm.[1,2] In addition, the kinetic-energy distribution of ^{258}Fm can be expressed as the sum of a low-energy and a high-energy component, whose mean energies differ by about 35 MeV. The mechanism behind this phenomenon, referred to as the bimodal fission, is the strong nuclear shell effects that emerge when the mass-symmetric fission fragments are near the doubly magic nucleus ^{132}Sn. The emergence of mass-symmetric divisions in ^{258}Fm is thus qualitatively explained if one takes into account the emergence of a fission path strongly stabilized by the fragment shell effect,[3] but quantitative understanding of the extremely narrow mass distribution has been less extensively studied.

So far, theoretical investigations have mainly focused on obtaining those fission paths by calculating the potential energy surface. In fact, theoretical models, such as the macroscopic-microscopic model,[4] the constrained Hartee-Fock+BCS (HFBCS) model,[5] and the constrained Hatree-Fock-Bogoliubov (HFB) model,[6] have successfully described such shell-stabilized path, that is, a path leading to mass-symmetric divisions with compact scission configurations, referred to as the compact symmetric path. In this sense, the energy-minimum path leading to the compact symmetric fission has been well established, but the structure of a *potential valley* along the path has not been clarified. As long as the fragment mass yield curve is concerned, it is necessary to obtain the potential energy curve at the scission configurations as a function of the fragment mass number.

We discuss the origin of the narrowness of the single peak at mass-symmetric division in the fragment mass-yield curve for spontaneous fission of ^{258}Fm[7]. For this purpose, we employ the macroscopic-microscopic model and calculate a potential-energy curve at the mass-symmetric compact scission configuration, as a function of the fragment mass number, which is obtained from the single-particle wave-function densities. In the calculations, we minimize total energies by varying the deformations of the two fragments, with constraints on the mass quadrupole moment, and by keeping the neck radius zero. The energies thus become functions of mass asymmetry. Using the obtained potential, we solve the one-dimensional Schrödinger equation with a microscopic coordinate-dependent inertial mass to calculate the fragment mass-yield curve, and estimate the mass yield curve originating from the compact symmetric valley.

An important point in the calculation is that the fragment masses are defined by the single-particle wave functions, rather than the macroscopic potential volumes. Using the Nilsson diagram at the scission point of the compact symmetric valley, we have shown that the mass numbers of two nascent fragments strongly depend on the single-particle configurations. In particular, the proton number of the fission fragments originating from the compact symmetric valley for ^{258}Fm is strongly constrained to $Z = 50$ due to the large shell gap. The calculated mass-yield curve is consistent with the extremely narrow experimental mass-yield curve. We obtain that the full width at half maximum for the fission fragments distribution originating from the compact symmetric valley is 3.6 u. For ^{258}Fm, it would be interesting to measure the ratio of protons to neutrons on the mass-yield curve, because the neutron distribution may be wider than the proton distribution, because the mean fragment neutron number is not magic. This would be a very strong test of the mechanism behind the narrow mass distribution.

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Neutron vortices in neutron stars

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[neutron vortices, neutron stars, superfluidity, glitches]

Since their discovery neutron stars have proved to be an exceptional laboratory where many aspects of physics not on earth can take place. One aspect of neutron stars that still has to be fully explained is the phenomenon of "glitches". A pulsar is a fast rotating neutron star whose period is very stable. The period decreases with time because of the constant energy emission of the star itself. During a glitch a pulsar undergoes a sudden angular velocity speed up, and then the frequency of the star undergoes a relaxation period after which the "normal" speed down rate is recovered. It has been proved that glitches are related to rearrangements of the structure of the star[2] and one of the most promising models[1] relates glitches to the superfluid present in the inner crust of the star. This superfluid is essentially decoupled from the rest of the star and acts as a reservoir of angular momentum. Since the angular momentum in a rotating superfluid is carried by the vortices that form therein investigation of the interaction between neutron vortices and the environment is of key importance in understanding the glitch phenomenon. According to a generally accepted picture, from the surface into the center of a neutron star the density increases and one encounters layers with a different structure. The outer crust of a neutron star is composed of heavy, neutron-rich nuclei, which get closer and closer until all neutron bound levels are filled and the drip line is reached. This represents the beginning of the inner crust, which extends from about $4.6 \cdot 10^{11}$ g/cm^3 to about $1.6 \cdot 10^{14}$ g/cm^3 (the saturation density in nuclei being $n_0 = 2.8 \cdot 10^{14}$ g/cm^3). The inner crust consists of a Coulomb lattice of nuclei embedded in a sea of free neutrons. The lattice step decreases with increasing density. We have limited ourselves to densities smaller than $n_0/4$, where nuclei can be assumed to be spherical. For such densities, the neutron sea should be superfluid, in keeping with the fact that the temperature of the neutron star should have dropped to about 0.01 MeV a few hundred years after its formation.

We have divided the inner crust into cylindrical cells where we have solved the Hartree Fock Bogoliubov equations with four different Skyrme interactions reproducing a vortex plus nucleus system. The result of the calculations shows that a vortex cannot form in the nuclear volume[3] at least at low and medium density,
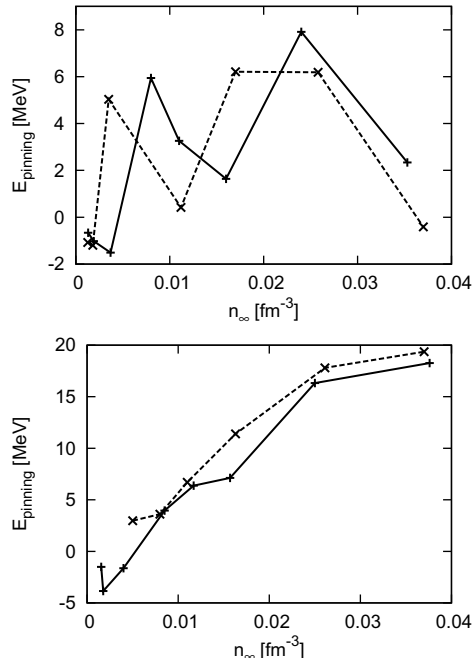
Fig. 1. Pinning energy for the SLy4 (solid) and SII (dashed) curves; (lower figure) the same but with SkM* (solid) and SGII (dashed) curves.

while at high density the choice of the Skyrme interaction adopted may change this picture (in particular the SkM* and SGII interaction lead to a vortex penetrating in the nuclear volume at high density, while for the SLy4 and SII interactions this is still forbidden). The impossibility a vortex penetrate the nuclear volume is shown by the complete suppression of the pairing gap in this region, which means that the region where the vortex and the nucleus are present is essentially no longer superfluid and thus the current flow is suppressed. The difference between the different Skyrme interactions is evident when calculating the energy to remove a vortex from a nucleus (the pinning energy) as shown in Fig [1].

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Direct reactions of antiproton and the black-sphere picture

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[Nuclear reaction, reaction cross section, nuclear radius, antiproton]

Nuclear size and mass are fundamental quantities characterizing the bulk properties of nuclei. Recently, for the purpose of deducing nuclear size from proton-nucleus elastic scattering and reaction cross sections, we proposed a model in which a nucleus is viewed as a "black" sphere of radius a.[1,2] Here we assume that the target nucleus is strongly absorptive to the incident proton and hence acts like a black sphere. Another requirement for the black-sphere picture is that the proton wave length is considerably smaller than the nuclear size. For proton incident energies higher than about 800 MeV, these requirements are basically satisfied. We showed that, for proton beams incident on stable nuclei, the cross section of a black sphere of radius a ($= \pi a^2$), which was determined by fitting the angle of the first peak calculated for proton elastic diffraction by a circular black disk of radius, a, to the measured value, is consistent with the measured total reaction cross section.[2] Furthermore, we confirmed that the black-sphere picture is valid down to about 100 MeV of an incident proton kinetic energy.[3,4]

This consistency suggests that the black sphere radius corresponds to a "reaction radius" inside which the reaction with incident protons occurs. Combining this fact with the notion of the "optical depth" of nuclei, which is defined by the ratio of the length of the proton trajectory inside the nucleus to the mean-free path of the proton, we constructed a formula for total reaction cross sections of proton-nucleus/nucleus-nucleus reactions, which is applicable for the reactions of wide region of mass and energy.[3]

In this work, we extend this black-sphere picture to the processes of several hadronic probes, such as antiprotons, pions, kaons, with stable nuclei. Although the black-sphere picture is originally expected to provide a decent description of the reaction cross section for any kind of incident particle that tends to be attenuated in nuclear interiors, whether this extension could make sense or not is not obvious.

As a first step, we systematically analyze the data of antiproton elastic scattering and reaction cross section for stable nuclei at the antiproton incident energies of lower than about 1000 MeV. The numerical results of σ_{BS} for antiproton-carbon(copper) are plotted in Fig. 1. They are consistent with the empirical values of σ_R although the values of σ_{BS} as well as σ_R contains large uncertainties. These preliminary results are encouraging, and the analyses of the data for other
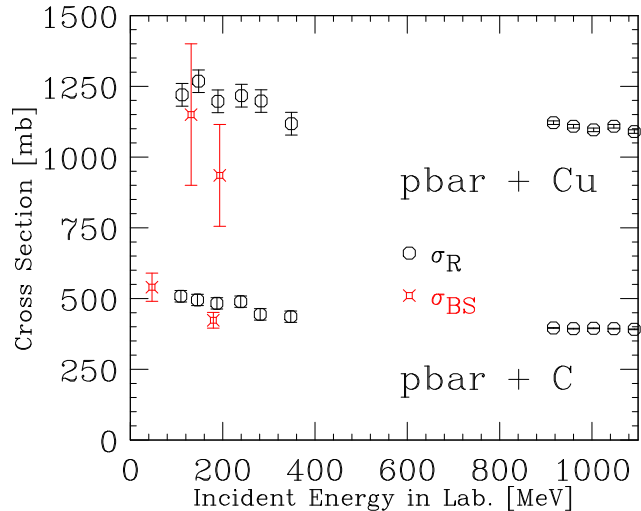
Fig. 1. Absorption cross section, $\sigma_{BS}(= \pi a^2)$, of an antiproton on a carbon(copper) target as a function of the incident kinetic energy of the antiproton. For comparison, we plot empirical data for the antiproton-carbon total reaction cross section, σ_R (○), whose references are found in Ref.[5].

hadronic probes are in progress.

In the energy region under consideration, the total cross sections of antiproton-proton are about five times larger than those of proton-proton, which implies shorter mean-free path of an antiproton than that of a proton at the same kinetic energy and the same nuclear density. According to the results of Ref.[3], protons are only sensitive to the nuclear surface, where the optical depth to the proton is the order of one.[3] Then, we can expect that an antiproton is sensitive to the outer surface of nuclei, where the optical depth to the antiproton is the order of one. This will open up a possibility of studying nuclear surface structure, which would control diffractive reactions, using several hadronic probes.

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Light Ξ hypernuclei in four-body cluster models†

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[hypernuclei, cluster model, hyperon-nucleon interaction]

In studies of nuclear interactions, two-body scattering data are the primary input for characterizing interaction models. However, $S = -1$ hyperon (Y)-nucleon (N) scattering data are very limited because of experimental issues. For $S = -2$ interactions such as $\Lambda\Lambda$ and ΞN, there are currently no scattering data. Therefore, the existing YN and YY interaction models have a substantial degree of ambiguity. Some YN scattering experiments will be performed at the Japan Proton Accelerator Research Complex (J-PARC) in the near future. Even in this facility, the possibility of performing ΞN or $\Lambda\Lambda$ scattering experiments is very limited or practically impossible. Hence, in order to obtain useful information on $S = -2$ interactions, studies of many-body, hypernuclear structure are indispensable.

Our intention in this work is to investigate the possible existence of Ξ hypernuclei and to explore the properties of the underlying ΞN interactions. Identification of Ξ hypernuclei in coming experiments at J-PARC will contribute significantly to understanding nuclear structure and interactions in $S = -2$ systems, which can lead to an entrance into the world of multi-strangeness. In order to encourage new experiments seeking Ξ hypernuclei, it is essential to make a detailed theoretical investigation of the possible existence of bound states, despite some uncertainty in contemporary ΞN interaction models. We investigate here the binding energies and structure of Ξ hypernuclei produced by (K^-, K^+) reactions on light targets on the basis of microscopic cluster models. One of the primary issues is how to choose the ΞN interaction. For this purpose, we adopted G-matrix ΞN interactions derived from the Nijmegen interaction models such as extended soft core model(ESC)[1] and Nijmegen model D (ND)[2], which gives rise to substantially attractive Ξ-nucleus potentials in accordance with the experimental indications. The interactions are represented as k_F-dependent three-ranged Gaussian form potential.

In this report, the structure calculations in $^7_\Xi$H and $^{10}_\Xi$Li are performed within the framework of the microscopic four-body cluster models using the Gaussian Expansion Method, since these light Ξ hypernuclei can be described in the framework of four-body cluster model.

The calculated energies in the $1/2^+$ ground state for $^7_\Xi$H($\alpha nn\Xi^-$) and 1^- and 2^- state for $^{10}_\Xi$Li($\alpha\alpha n\Xi^-$)

using ESC are demonstrated in Fig.1 as a function of k_F.

In A=7 hypernucleus, the four-body calculation predicts the existence of nuclear bound states in ESC case at reasonable k_F values of around 0.9 fm^{-1}. It is interesting to note that the addition of two neutrons to the $\alpha\Xi^-$ system gives rise to about 1.3 MeV more binding energy. The same tendency is seen in ND.

In A=10 hypernucleus, we have obtained the nuclear Ξ^- bound states as a result of careful four-body calculations with $k_F \sim 1.0$ fm^{-1}. Furthermore, we have similar binding energies of the $J = 2^-$ state for both the ESC and ND interactions.

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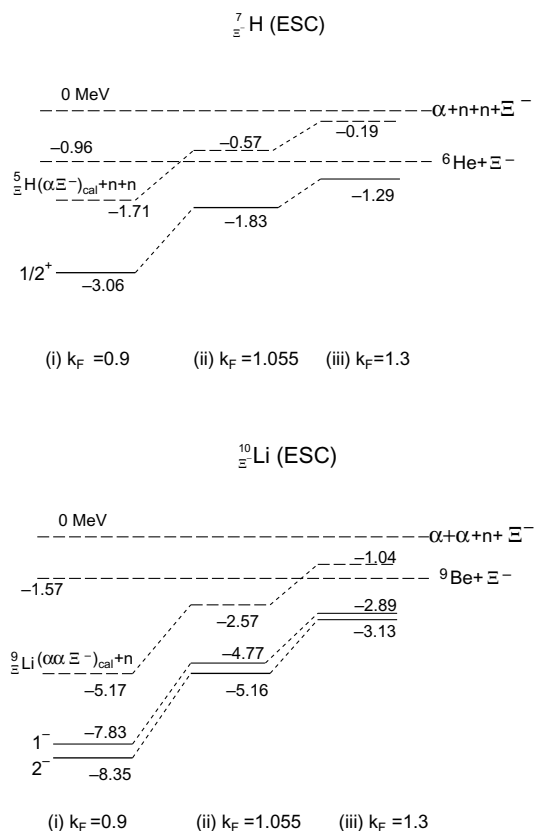
Fig. 1. Calculated energy levels of (a) $^7_\Xi$H and (b)$^{10}_\Xi$Li for three k_F values using ESC.

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$p\Xi^0$ force studied with lattice QCD[†]

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[Lattice QCD, Hyperon-nucleon interaction, Nuclear forces, Hypernuclei]

Study of the baryon-baryon interaction is an important subjects in the nuclear physics. The present hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions have large uncertainties despite these interactions playing important roles in high density nuclear systems such as interior of neutron stars. For example, no reliable phase shift analysis of the ΛN scattering has as yet been performed experimentaly so that different phaseshifts have been predicted by different theoretical works. In principle, the interaction should be understood in terms of the dynamics of quarks and gluons, namely quantum chromodynamics (QCD).

We study the $p\Xi^0$ force by using quenched lattice QCD. The Bethe-Salpeter amplitude is calculated for the lowest scattering state of the system so as to obtain the $p\Xi^0$ potential. The numerical calculation is performed with $\beta = 5.7$, the lattice spacing of $a = 0.1416(9)$ fm, on the $32^3 \times 32$ lattice. The spatial lattice volume is $(4.5 \text{ fm})^3$. Two kinds of ud quark mass are used, corresponding to $m_\pi \simeq 0.37$ GeV and 0.51 GeV. Tables 1-2 compare the hadron masses calculated from the lattice QCD with the experimental values. Figure 1 shows the effective central potential, obtained from the wave function at the time slice $t - t_0 = 6$ with the hopping parameter $\kappa_{ud} = 0.1678$, corresponding to $m_\pi \simeq 0.37$ GeV. The scattering length is obtained from Lüscher's formula.[2] As is seen in Figure 2, the $p\Xi^0$ interaction is both attractive at $^1S_0$ and $^3S_1$ channels, and the interaction in the $^3S_1$ is more attractive than in the $^1S_0$. These attractive forces become stronger as the u, d quark mass decreases.

We are also calculating the $p\Lambda$ potential by using $(2 + 1)$-flavor PACS-CS gauge configuration[3], which will be reported elsewhere.

Table 1. Meson masses in the unit of MeV. The numbers in parenthesis show the errorbar in the last digit.

κ_{ud}	N_{conf}	m_π	m_ρ	m_K	m_{K^*}
0.1678	1283	368(1)	813(4)	554.0(5)	884(2)
0.1665	1000	511.2(6)	861(2)	605.3(5)	904(2)
Exp.		135	770	494	892

Table 2. Baryon masses in the unit of MeV. The numbers in parenthesis show the errorbar in the last digit.

κ_{ud}	N_{conf}	m_N	m_Λ	m_Σ	m_Ξ
0.1678	1283	1167(7)	1266(6)	1315(6)	1383(6)
0.1665	1000	1300(4)	1354(4)	1375(4)	1419(4)
Exp.		940	1116	1190	1320

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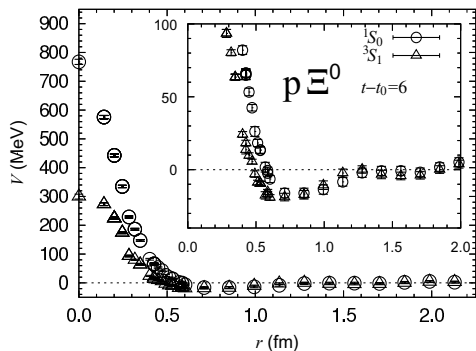
Fig. 1. The effective central potential for $p\Xi^0$, in the $^1S_0$ (circle) and $^3S_1$ (triangle), obtained from the wave function at time slice $t - t_0 = 6$. The hopping parameter $\kappa_{ud} = 0.1678$ is used for the u, d quark. The inset shows its enlargement.
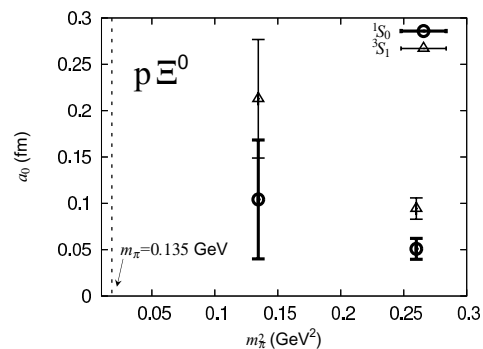
Fig. 2. The scattering lengths for $p\Xi^0$ in the $^1S_0$ (circle) and $^3S_1$ (triangle) as a function of m_π^2. The dashed line shows the physical point at $m_\pi = 0.135$ GeV.

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Hadro-Chemistry for High Momentum Probes of Heavy Ion Collisions[†]

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[Heavy ion collisions, quark gluon plasma]

Jet quenching, the suppression of hadrons emitted at high momentum p_T, has been one of the key discoveries in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC). It has been interpreted as the energy loss of fast quarks or gluons traveling through quark gluon plasma. It is a main signature for the creation of a quark gluon plasma[1]. Energy loss is characterized by the transport coefficient $\hat{q} = \mu^2/\lambda$, the momentum transferred squared per mean free path λ.

In a series of papers in 2008 we have argued that measurements of the suppression and elliptic flow of identified hadrons at high transverse momentum p_T can lead to novel and complimentary information about the medium created in nuclear collisions. In principle, the mean free path λ can be extracted independent of $\hat{q}$. In simple terms, this is possible because the processes between jets and the medium which change the chemical composition are generally independent of the momentum transfer in the process.

We use a model in which a sample of leading jet partons is propagated through a fireball parameterization. Partons lose energy, described by a Fokker-Planck equation, at a rate fitting the single inclusive nuclear suppression ratio R_{AA}. In addition, the jet particles are subject to rate equations

$$\frac{dN^a}{d\tau} = -\sum_b \Gamma^{a \to b} N^a + \sum_c \Gamma^{c \to a} N^c \qquad (1)$$

in which conversion rates Γ between flavors a, b, c are given by leading order elastic cross sections. We evolve samples of up, down and strange quarks as well as gluons and photons. Conversions of jets into photons have been discussed in the past[2] and it was recognized that this might be an important contribution to the total photon yield. Heavy quarks are taken into account with slight modifications reflecting the mass threshold.

We first revisit the issue of the relative suppression of protons and pions. It was pointed out that protons fragment predominantly off gluon jets, while pions prefer quark jets. Quenching of gluons and quarks is related via a color factor 9/4 which leads to the naive expectation that protons should exhibit stronger quenching than pions at high p_T. This is not observed at RHIC. It was first pointed out by Liu, Ko and Zhang that this can be explained naturally if the flavor of a jet parton is not conserved[3]. They can explain the proton/pion ratio with conversions of quarks into gluons and vice versa, essentially rendering the concept of a fixed jet flavor invalid. We confirm the results of Liu et al. and suggest a novel double ratio observable, the ratio of the R_{AA}s for protons and pions as a very sensitive quantity for conversion processes. We also find a rate for conversion photons which is consistent with the experimental results.

As a novel idea we propose to use strangeness as a signal for jet conversions and as a strong candidate for a measurement that could constrain the mean free path. Strangeness at RHIC energies is marginal in the jet sample, $s/(u+d) \approx 5\%$ while it is chemically equilibrated in the plasma. The coupling between jets and medium will increase the amount of strange quark jets and should result in a relative enhancement of kaons compared to pions at high p_T. Finding and measuring the size of this enhancement would be an important step to quantify jet medium interactions.

At LHC, strangeness is already equilibrated in the initial jet sample due to the higher center of mass energy and the importance of initial flavor-blind $g + g$ fusion process. Hence we predict no additional strangeness enhancement at LHC energies. We have a similar negative result for charm and bottom quarks at both RHIC and LHC energies. The reason for this is the lack of chemical equilibration of heavy quarks even in the bulk. Therefore the chemical gradient between jets and medium is small. Of course, this result is consistent with heavy quark measurements at RHIC.

Finally, we discuss the implications of flavor conversions for elliptic flow v_2. Conversion particles should lead to a negative contribution to v_2, as was first discovered for conversion photons[4]. We could show that this mechanism is also active for strange quarks at RHIC and should lead to an observable suppression of kaon v_2 at high p_T compared to pion v_2.

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3. Hadron Physics

Absolute luminosity determination using the vernier scan technique at $\sqrt{s} = 62.4$ GeV

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Measured cross sections in the PHENIX experiment[1] are normalized to the integrated luminosity for the analyzed data sample, L, which is determined from the number of events triggered by beam-beam counters (BBCs) using an absolute calibration of the BBC trigger cross section obtained via the van der Meer or Vernier scan technique[2]. In a scan, the transverse widths of the beam overlap are measured by sweeping one beam across the other in steps while monitoring the BBC trigger rate. This information and the bunch intensities of the two beams measured by Wall Current Monitors (WCMs) are used to compute the instantaneous machine luminosity L_{machine}[2]. The BBC trigger cross section is the ratio of the BBC trigger rate when the beams are overlapping maximally to the effective luminosity $L_{\text{eff}} = L_{\text{machine}} \cdot \epsilon_{vertex}$, where ϵ_{vertex} is the fraction of the number of collisions in PHENIX interaction region (IR) within BBC trigger vertex cut (usually $|z| < 30$ cm).

In $p+p$ collisions at $\sqrt{s} = 62.4$ GeV, the BBC trigger efficiency vs z shape was estimated from the comparison with a "detector unbiased" z-vertex distribution obtained from the convolution of colliding bunch intensity profiles along the z-axis as measured by WCMs. The correction factor of 0.83 ± 0.08 was obtained, resulting in $\epsilon_{vertex} = 0.37 \pm 10\%$. This approach is confirmed in $p + p$ collisions at $\sqrt{s} = 200$ GeV where zero degree calorimeters (ZDCs) have enough efficiency to measure the z vertex distribution. The efficiency of the ZDCs (located at $z = \pm 18$ m) does not depend on collision vertex position in PHENIX IR, which was distributed with a sigma of 0.5–0.7m around $z = 0$. The vertex distribution obtained with the WCMs is well reproduced by the measurement with the ZDCs at $\sqrt{s} = 200$ GeV (Fig. 1(a)).

Beam focusing in the IR leads to bunch transverse sizes that vary away from the collision point ($z = 0$) as $\sigma^2(z) = \sigma^2(z = 0) \times (1 + z^2/\beta^{*2})$. This is so-called hourglass effect. The correction due to this effect for vernier scan data at $\sqrt{s} = 62.4$ GeV with a betatron amplitude function at the colliding point of $\beta^* = 3$ m was simulated with WCM data and calculated to be 0.93 ± 0.02. The applicability of our calculation technique is illustrated in Fig. 1 with the high statistics vernier scan data at $\sqrt{s} = 200$ GeV.

Figures 1(b) and 1(c) shows the sensitivity of our data for the transversely displaced beams to crossing angle between colliding beams. Two peaks in Figs. 1(b) and 1(c) show overlap of diverged colliding beams by the hourglass effect at large z in displaced collisions of the vernier scan. In all vernier scan measurements, the crossing angle was found to be less than 0.2 mrad, which translates to a negligible correction for L_{machine} at $\sqrt{s} = 62.4$ GeV with a typical bunch length of ~ 1 m and bunch transverse size of 1 mm.

Due to limited amount of data collected at $\sqrt{s} = 62.4$ GeV, systematic uncertainties of vernier scan technique are thoroughly studied in abundant set of $\sqrt{s} = 200$ GeV vernier scan data on bunch-by-bunch level. After all corrections discussed above, our BBC trigger cross section in $p + p$ collisions at $\sqrt{s} = 62.4$ GeV is found 13.7 mb with a systematic uncertainty of ± 1.5 mb ($\pm 11\%$). A systematic uncertainty of 4% is assigned for the run-by-run error in the vernier scan analysis at $\sqrt{s} = 200$ GeV, 10% for BBC trigger efficiency correction of ϵ_{vertex}, and 2% for hour-glass correction.

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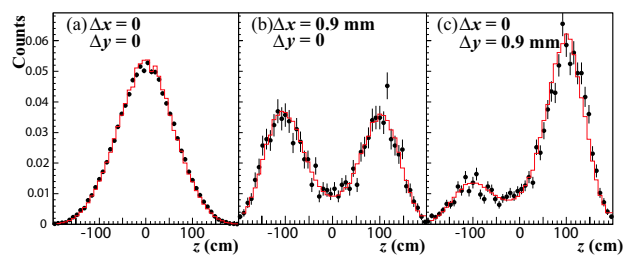
Fig. 1. Collision z-vertex distribution in PHENIX IR measured by ZDCs in a vernier scan at $\sqrt{s} = 200$ GeV (points) and calculations from convolution of colliding bunch intensity profiles along z-axis and including the hourglass effect for bunches with typical length of 1 m and transverse size of 0.3 mm (histograms); a) beams are head-on; b) one beam is 0.9 mm displaced relative the other beam in horizontal direction and c) one beam is 0.9 mm displaced relative the other beam in vertical direction, calculations include bunch crossing angle in vertical projection of 0.15 mrad.

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Cross Section For Prompt Photon Production
in Proton-Proton Collisions at $\sqrt{s} = 62.4$ GeV

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Prompt photon production[1)2)] in high energy proton-proton collisions is expected to be useful to test the applicability of perturbative Quantum Choromo-Dynamics (pQCD) to predict other quantities of interest, such as double helicity asymmetry A_{LL}. The A_{LL} is defined as;

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}. \tag{1}$$

$\sigma^{++(+-)}$ is a cross section for particle production such as a prompt photon in the proton-proton collision with beam helicity pattern "$++ (+-)$". Once the applicability of pQCD is confirmed, the framework of pQCD can be used to determine gluon spin contribution to the proton spin Δg from A_{LL}.

In proton-proton collisions, the prompt photon is mainly produced via quark-gluon collision and quark-anti-quark annihilation. The cross section for prompt photon production is defined as

$$E \cdot \frac{d^3\sigma}{dp^3} \sim \frac{1}{2\pi \cdot L \cdot p_T \cdot \varepsilon} \frac{\Delta N_\gamma}{\Delta p_T \cdot \Delta \eta} \tag{2}$$

where ΔN_γ is yields per the unit of transverse momentum p_T and the unit of pseudo-rapidity η. L is the integrated luminosity, and ε is the correction factor described in the following paragraphs.

We measured the cross section for prompt photon production from proton-proton collisions at $\sqrt{s} = 62.4$ GeV in a PHENIX experiment. The data was collected in 2006 with the PHENIX central arm spectrometer. The PHENIX central arm spectrometer consists of two arms which are placed almost back-to-back on their azimuth. Each arm covers pseudo-rapidity $|\eta| < 0.35$ and 90 degree azimuthal angle. Photons with energy above 0.15 GeV are measured using the electromagnetic calorimeters (EMCal). Charged particles are identified with the pad chamber. The integrated luminosity is about 0.065 pb^{-1}, which corresponds to 894 M events. In this analysis, $p_T > 2$ GeV/c photons are required to exist for each event in the offline analysis.

Prompt photons are extracted by subtracting background photons from inclusive photons. The background photons mainly come from π^0 decay. Therefore, it is important to evaluate the π^0 decay photons precisely. The π^0 decay photons are categorized into two groups. If both of the photons are detected, they are called "two tag photons". If only one of the two photons is detected, due to the limited acceptance of the EMCal, it is called a "one tag photon". The π^0 decay photons in the two tag photons are identified

with an invariant mass by reconstructing the four momenta of two photons. On the other hand, the π^0 decay photons in the one tag photons are estimated using a fast Monte-Carlo simulation and the experimental data. Then, the contribution of decay photons from other particles such as η, ω and η' is also estimated.

The prompt photon yields are normalized with the integrated luminosity, and are corrected for the efficiency of EMCal etc. to obtain the cross section (Eq.2). Figure 1 shows the cross section with systematic uncertainties, and a comparison of the present data with the Next-to-Leading Order (NLO) pQCD calculation. The main systematic uncertainty at low p_T comes from extraction of π^0 yields from the sample including misidentified particles. It means that it is not π^0 but is accidentally regarded as π^0. The prediction of the NLO pQCD calculation at low p_T region is lower than experimental values. It suggests a need to take into account further higher order terms in the calculation. On the other hand, at high p_T region, both values agree with each other within the uncertainties of measurement and calculation.
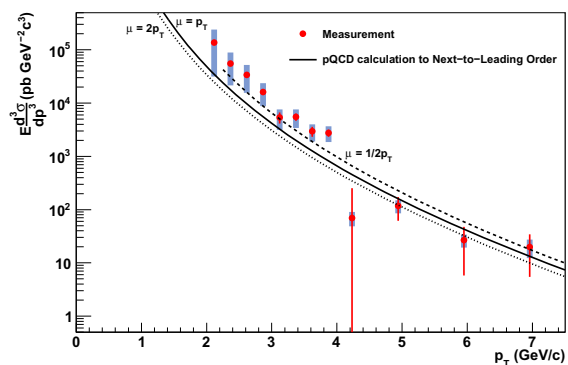
Fig. 1. The cross section for prompt photon production as a function of p_T with statistical uncertainties (red) and systematic uncertainties (blue) compared with the NLO-pQCD calculation. The three lines represent the calculation with different scales.

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Double spin asymmetries of open heavy-flavor production in forward rapidity with polarized p + p collisions at $\sqrt{s}$=200GeV

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[Open heavy flavor, spin, asymmetry]

Deep-inelastic scattering (DIS) experiments with polarized leptons and polarized nucleons have shown that the spins of quarks and anti-quarks account for only approximately 25% of nucleon spin.[1] The rest of the proton spins must be carried by the gluons and orbital angular momentum. Measurements of the scale dependence of the inclusive nucleon spin structure function and recent semi-inclusive DIS data[2] have shown the coarse constraint in the possible gluon spin contribution. Furthermore, heavy quark production in polarized p+p collision at RHIC energy is dominated by the gluon-gluon interaction, thus providing direct access to the (polarized) gluon distribution in the proton. Compared with the current double spin asymmetry of π^0[3], inclusive jet[4] and photon measurement at RHIC, heavy flavor provides a very independent channel to study gluon polarization.

With the current PHENIX detector, open heavy flavor measurement in the muon arms is limited to indirect statistical measurement. Extraction of signal muons in this analysis is predicated upon successful estimation and statistical subtraction of all background sources which are defined to be tracks not resulting from the semi-leptonic decay of heavy flavor mesons. The "inclusive tracks" are defined as tracks penetrating the muon-identifier detector (MuID) and consist of muons from heavy-flavor decay, muons from decay of light hadrons (K and π) and some light hadrons which punched through the MuID. The "hadron tracks" are defined as tracks stopping in the MuID and consist mostly of light hadrons according to our simulation studies.[5]

Our strategy to extract the asymmetry of muons from the heavy-flavor decay is to 1) estimate background asymmetry with "hadron tracks", and 2) subtract the background asymmetry from the asymmetry of "inclusive tracks".

The asymmetries of "inclusive tracks" and "hadron tracks" are given as

$$A_{LL}^{incl/hadron} = \frac{1}{P_B \cdot P_Y} \frac{N_{incl/hadron}^{++} - R \cdot N_{incl/hadron}^{+-}}{N_{incl/hadron}^{++} + R \cdot N_{incl/hadron}^{+-}} \quad (1)$$

where P_B and P_Y are the polarization for blue and yellow beams respectively. $N_{incl/hadron}^{++}$ ($N_{incl/hadron}^{+-}$) is the number of "inclusive tracks" or "hadron tracks" from the same (opposite) helicity beam collisions. $R = L^{++}/L^{+-}$ is the luminosity ratio of the same helicity

beam collision to the opposite helicity beam collision. The A_{LL} of signal muons from the heavy-flavor decay can be derived from

$$A_{LL}^{signal} = \frac{A_{LL}^{incl} - r \cdot A_{LL}^{BG}}{1 - r}, \quad (2)$$

$$\delta A_{LL}^{signal} = \frac{\sqrt{(\delta A_{LL}^{incl})^2 + r^2 \cdot (\delta A_{LL}^{BG})^2}}{1 - r} \quad (3)$$

where r is the background fraction and $A_L L^{BG}$ is the background asymmetry for which $A_L L^{hadron}$ are used.

The background fraction was calculated from the p+p run in the year 2005 single muon analysis.[6] Figure 1 shows the double spin asymmetry results for muons from heavy flavor decays from the data for the runs in 2005 and 2006.
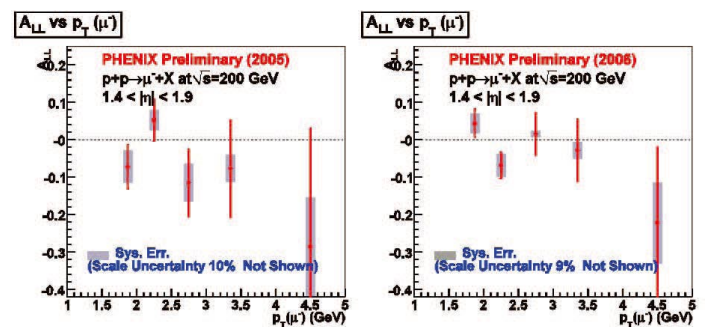
Fig. 1. Double spin asymmetry A_{LL} for μ^- from heavy flavor decay as a function of p_T from p+p runs in 2005 and 2006, with averaged polarization 50% and 60%, respectively. Error bars show statistical errors and shaded error bands show systematic errors.

No nonzero A_{LL} has been observed at the current precision. Our results are limited by statistics. It is important to measure the A_{LL} of heavy flavor production for gluon polarization determination using an independent physics process with different systematic uncertainties and confirm the universality of the gluon polarization measurement.

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Measurement of transverse single-spin asymmetry with J/Ψ in polarized p+p collisions at $\sqrt{s} = 200$ GeV

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[Spin, J/Ψ, asymmetry]

The spin structure and its investigation of the proton has revealed itself to be extremely complex, and is an active area of ongoing research. Large transverse single-spin asymmetries in inclusive particle production at fixed target energies[1] were observed in forward pion production by the E704 collaboration at FERMILAB ($\sqrt{s} = 19.4$ GeV). Such large asymmetries were initially surprising due to the prediction of pQCD in leading order that these asymmetries should be small. Interest has recently grown with the discovery by STAR[2] and BRAHMS[3] that these asymmetries persist even at RHIC energies. Transverse single-spin asymmetries (SSAs), A_N, have the potential to be an important tool in understanding the quark and gluon spin distributions in a polarized proton. Precision measurement of SSAs in different kinematic regions with various particles and their QCD analysis may serve to quantify contributions from different mechanisms. In a theoretical model calculation by Feng Yuan, the SSA is found to be very sensitive to the production mechanism of heavy quarkonium, where the production has been studied using non-relativistic QCD (NRQCD) and the heavy quark pairs are produced at a short distance in color-singlet or color-octet configurations[4]. According to this model, the SSA in ep scattering vanishes if J/Ψ is produced in the color-singlet channel but survives in the color-octet channel. However, in pp scattering the SSA vanishes if J/Ψ is produced through the color-octet channel but survives in the color-singlet channel.

The J/Ψs have been measured with PHENIX muon spectrometers which cover the forward rapidity range of $1.2 < |\eta| < 2.4$. At RHIC energies, heavy flavor production is dominated by the gluon-gluon interaction; thus the Collins effect has minimum impact on A_N as the gluon's transversity is zero. Therefore, heavy flavor A_N in transversely polarized p+p collisions at the PHENIX experiment offers a good opportunity to gain information on transverse momentum dependent gluon distribution which can be described by gluon's Sivers function[5].

The left-right single-spin asymmetry A_N is calculated by:

$$A_N = \frac{1}{P_b}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} = \frac{1}{P_b}\frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}} , \quad (1)$$

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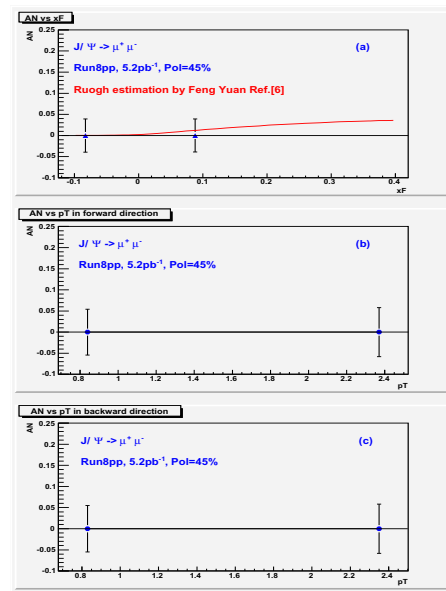
Fig. 1. Expected precision for A_N versus (a) x_F, (b) p_T in forward rapidity and (c) p_T in backward rapidity

where P_b is the beam polarization, $\sigma^\uparrow$ ($\sigma^\downarrow$) is the production cross section when the proton in the bunch is polarized up (down), and $N^\uparrow(N^\downarrow)$ is the J/Ψ yield from up (down) polarized bunches.

Here, we report our inclusive analysis with $J/\Psi \rightarrow \mu^+\mu^-$. The expected statistical uncertainties of A_N in J/Ψ production for the data collected in 2008 ($L = 5.2pb^{-1}, P_b \sim 45\%$) are shown in Fig. 1 as a function of x_F and p_T in both forward and backward rapidities. The model calculation shown in Fig. 1 plot (a) assumes the gluon's Sivers function is $0.5x(1-x)$ times the unpolarized gluon distribution and 30% of J/Ψ comes from feed down of χ_c[6]. Future high statistic measurement of A_N in J/Ψ production offers a good opportunity to study the heavy quarkonium production mechanism and gluon's Sivers function.

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Study of J/ψ spin alignment in proton-proton collisions at $\sqrt{s} = 200$ GeV in RHIC PHENIX experiment

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[nucleon structure, J/ψ, spin alignment, polarization]

Non-relativisitic quantum chromodynamics (NRQCD) calculations taking into account color octet models (COMs)[1] have succeed in describing the production cross section of heavy quarkonia measured by CDF and other experiments[2,3]. However, the models can not reproduce experimental data with respect to J/ψ spin alignment[4]. The CDF experiment reported small longitudinal polarization while NRQCD models predict transverse polarization at high transverse momenta. Understanding of heavy quarkonium production mechanism has not proceeded well due to the smal number of experimental measurements.

The J/ψ spin alignment is determined experimentally by measuring decay angular distribution of leptons in the J/ψ rest frame. The angular distribution is parametrized with polar angle θ which is the angle between lepton momentum in J/ψ rest frame and J/ψ momentum in the laboratory frame (helicity frame).

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda\cos\theta, \qquad (1)$$

where $\lambda = 0$ indicates non-polarization. Positive and negative values of λ correspond to transverse and longitudinal polarization, respectively.

A proton-proton collision experiment is in progress at the relativistic heavy ion collider (RHIC) operated at Brookhaven National Laboratory. The PHENIX experiment[5] at the RHIC has muon spectrometers (Muon Arm) to detect J/ψ via $\mu^+\mu^-$ channel. The PHENIX Muon Arm covers forward rapidity regions with $1.2 < |\eta| < 2.2$ and $\Delta\phi = 2\pi$. Study of J/ψ spin alignment in proton-proton collisions at $\sqrt{s} = 200$ GeV is ongoing with several ten thousands J/ψ events accumulated at the PHENIX Muon Arm. We have small acceptance in $|\cos\theta| \sim 1$ because decay muons emitted backward in J/ψ rest frame are not boosted well enough to penetrate materials for hadron background rejection. Thus acceptance studies of a Muon Arm with a Monte-Carlo simulation have an important role in measuring J/ψ spin alignment.

Figure 1 shows simulated angular distributions of J/ψ decay muon at PHENIX Muon Arm. The simulation was performed for an unpolarized case ($\lambda = 0$) and extreme cases ($\lambda = \pm 1$). J/ψ events are generated as the simulation reproduces reconstructed J/ψ transverse momentum and rapidity distributions of real data. Expected statistical errors of real data are also shown on the points of $\lambda = 0$. The distribution of
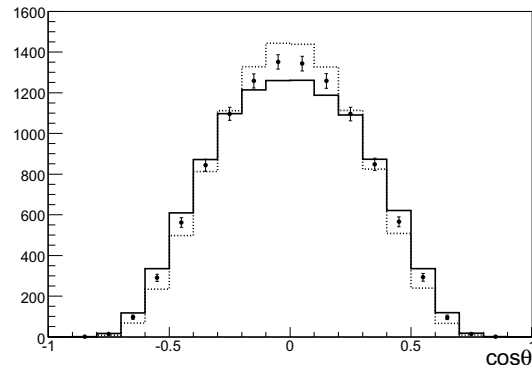
Fig. 1. Simulated angular distributions of J/ψ decay muon at the PHENIX Muon Arm. Simulation results from non-polarization ($\lambda = 0$) are shown as black points with expected statistical errors of data. Solid and dashed histograms are for $\lambda = +1$, -1, respectively.

the transversely polaraized case ($\lambda = +1$) is broader than the that of the longitudinal one ($\lambda = -1$) as expected from the expression of (1).

¿From the acceptance study, we can expect that the statistical accuracy of the current data set is enough to discuss J/ψ spin alignment.

Study of J/ψ spin alignment at RHIC PHENIX is ongoing. We hope to finalize the results soon. So far, an anisotropy in the helicity frame has been considered in this study. Recently, the necessity of analyzing data with respect to other frames, such as the Collins-Soper[6] or the Gottfried-Jackson[7] frame is being discussed because the proper polarization axis which is sensitive to a physics phenomenon is not known well. Moreover, measurements not only of polar angular distribution but also of azimuthal one are important. We will access these measurements in the future.

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Measurement of direct photon using a virtual photon method in $\sqrt{s} = 200$ GeV p+p collisions at RHIC-PHENIX

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[Direct photon, virtual photon method, Low pT]

Direct photon is a unique probe to investigate properties of Quark Gluon Plasma (QGP) since photons penetrate the dense and hot partonic matter created by heavy ion collisions. Special interest is given to thermal photons from the QGP which are considered to be the primary contributor at the low energy region in the inclusive photon spectrum.[1]

A measurement of 'real' direct photon using an electromagnetic calorimeter is notoriously difficult below 4 GeV since systematic errors cannot be reduced due to the large hadron background, particularly π^0. Recently an alternative method using a 'virtual' direct photon measurement, i.e, a measurement of e^+e^- pairs from 'virtual' direct photon decays was demonstrated to provide the photon yield with less systematic error in both p+p and Au+Au collisions[2] shown as Fig. 1. A clear excess over the binary scaled p+p result (shown
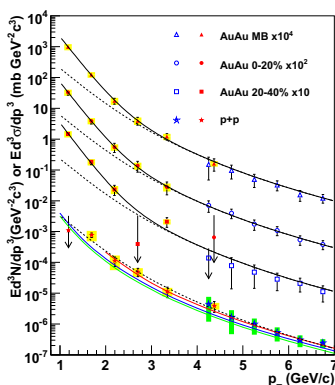
Fig. 1. The direct photon spectra in p+p and Au+Au collisions as a function of p_T.

by the dotted line) is seen in Au+Au collisions for $1 < p_T < 3$ GeV/c, and a hydrodynamical calculation indicates that this excess comes from thermal radiation from QGP.[3] Thus it is very important to measure the direct photon yield in p+p collisions more precisely for $1 < p_T < 3$ GeV/c in order to evaluate the mean contribution of the thermal photons. The data on p+p collisions taken in 2006 is available and its statistics are about twice that of the one already analyzed. This report describes the current status of the analysis in $\sqrt{s} = 200$ GeV p+p collisions at RHIC-PHENIX using the data taken in 2006.

All electrons and positrons in the same event are combined into pairs. The obtained e^+e^- pair mass

distribution contains several components from different sources, which are listed below.

- Virtual direct photon decays
- Hadron decays
- Photon conversions
- Combinatorial background
- Cross pairs from $\pi^0, \eta \rightarrow 2\gamma(\text{or } \gamma e^+e^-) \rightarrow e^+e^-e^+e^-$

The pairs from photon conversions are removed by a cut on the orientation of the pair in the magnetic field[4]. The combinatorial background is computed with a mixed-event technique and subtracted. The contributions from hadron decays are estimated using a hadronic cocktail simulation, which incorporats the measured yields of the hadrons at PHENIX. The effects on real data such as several efficiencies, geometrical acceptance and momentum smearing are considered in the cocktail simulation through the GEANT 3 based simulator of the PHENIX detector. The cross pairs are evaluated by comparing a like-sign pair distribution between the real and simulated one. Figure 2
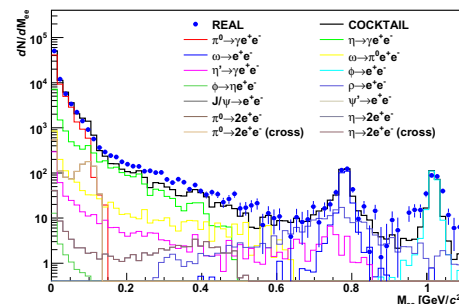
Fig. 2. Comparison of the e^+e^- pair mass distribution between the real and the cocktail simulation.

shows the comparison of the e^+e^- pair mass distribution between the real (blue symbols) and the cocktail simulation (black line). The real data is in good agreement with the cocktail simulation.

The virtual direct photon fraction to inclusive virtual photon yield will be evaluated from the excess over the cocktail simulation for several p_T regions and then the real direct photon yield will be determined from the obtained virtual direct photon fraction.

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Longitudinal Double Spin Asymmetry for Inclusive Jet Production in Polarized p+p Collisions at 200 GeV

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[gluon polarization, jets, longitudinal double spin asymmetry, STAR]

The RHIC spin program uses polarized p+p collisions to study ΔG, the integral of the gluon polarized distribution function, $\Delta g(x, Q^2)$. There are many processes where the gluon participates directly thus ΔG can be probed directly and more precisely than previously attained. This contribution reports on the inclusive jet production asymmetry measurement at the Solenoid Tracker at RHIC (STAR) experiment[1]. The inclusive jets channel is an excellent tool to study the gluon polarization due to its large cross section and relative independence from fragmentation functions.

In 2005 we had an order of magnitude increase in the figure of merit over our previous measurements[2] with coverage in jet p_T up to 30 GeV/c. This allowed us to perform a quantitative comparison of our measured results[3] to global fits of polarized deep-inelastic scattering (DIS) data within the GRSV framework[4] for various fixed values of ΔG[5]. These comparisons showed that the global fits that predict very large ΔG values and large A_{LL} are excluded[3].
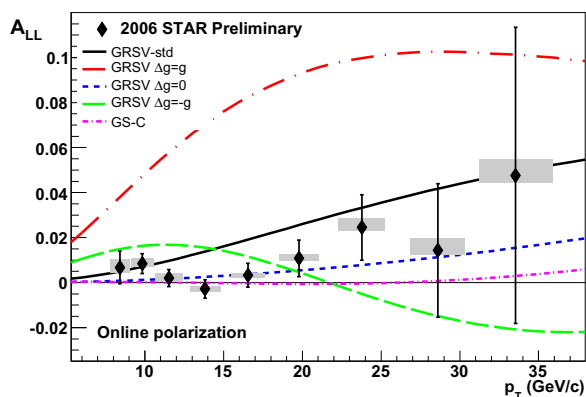
Fig. 1. Preliminary 2006 A_{LL} for inclusive jet production at $\sqrt{s} = 200$ GeV versus jet p_T, where the error bars are statistical and the gray bands indicate the systematic uncertainties.

Figure 1 shows preliminary 2006 A_{LL} versus jet p_T corrected for detector response. The points with error bars are the data with statistical uncertainties. The gray shaded band represents the systematic uncertainties, excluding the 25% uncertainty on the beam polarization values. Figure 1 also shows NLO pQCD calculations which incorporate different scenarios for

$\Delta g(x)$, including the best global fit to the inclusive DIS data (std)[4]. The other curves include maximally positive gluon polarization ($\Delta g(x) = g(x)$) at the input scale, maximally negative gluon polarization ($\Delta g(x) = -g(x)$), and zero gluon polarization ($\Delta g(x) = 0$). In addition, it includes a prediction derived from GS-C[6] which has a large positive gluon polarization at low x, a node near $x \sim 0.1$, and a negative gluon polarization at large x. The statistical uncertainties in the 2006 A_{LL} measurements at high p_T are a factor of 3 to 4 smaller than they were in the 2005 data[3], which leads to significantly more stringent constraints on gluon polarization models.

These results were included in a recent "global" NLO analysis, DSSV[7], the first analysis to include inclusive DIS, semi-inclusive DIS, and RHIC pp collision data together. The result of this analysis showed that $\Delta g(x, Q^2)$ is small in the accessible range of momentum fraction, with a possible node in the distribution near $x \sim 0.1$, basically evolving away at higher scales with the opposite phase from GS-C. A study of the DSSV χ^2 profile and the partial contributions $\Delta \chi^2$ of the individual data sets shows that these STAR data provide the strongest limits on negative gluon polarization over the range $0.05 < x < 0.2$ and also contribute significantly to the limits on positive gluon polarization over the same range.

In summary, A_{LL} measurements from inclusive jet data from 2005 and 2006 are reported. These results provide significant constraints on the gluon spin contribution to the proton spin when compared to NLO pQCD calculations. They play a significant role in the first global NLO analysis to consider DIS, SIDIS and RHIC data together.

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Measurement of Transverse Single Spin Asymmetry of Open Heavy Flavor in Polarized p+p Collisions at PHENIX

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[Spin, Asymmetry]

The transverse spin structure of the proton is still poorly understood. The measurement of transverse single spin asymmetries gives us an opportunity to probe the quark and gluon structure of transversely polarized nucleons. At RHIC energy, heavy flavor production is dominated by gluon-gluon fusion, so the Collins effect (transversity distribution in combination with spin-dependent fragmentation function) has minimum effects on transverse single spin asymmetry (A_N) as the gluon's transversity is zero. The measurement of A_N in heavy flavor production is thus particularly sensitive to the gluon Sivers distribution (transversely asymmetric k_T gluon distributions) which is related to the orbital angular momentum of gluons inside the polarized protons.

In this report we present the first measurement of A_N in single muons from open heavy flavor decay production in transversely polarized p+p collisions at $\sqrt{s}$=200GeV. The muons are measured with muon spectrometers in full azimuthal coverage at forward rapidities ($1.2 < |\eta| < 2.4$).

The single muons from semi-leptonic decay of open heavy flavor are measured through the statistical subtraction of background sources, with the remaining yield attributed to open heavy flavor decays. The sources of backgrounds are: (1) muons from light hadron decay before reaching the pre Muon Tracker (MuTr) absorber; (2) punch through hadrons which penetrate the 1.5m of steel absorber to reach the deepest layer of MuID; (3) background tracks which dominated by hadron which decay into a muon after reaching the MuTr. The detail of how to estimate the background contributions can be found in[1].

Transverse single spin asymmetry A_N is measured as

$$A_N = \frac{1}{P_b}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} = \frac{1}{P_b}\frac{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} - \sqrt{N_L^\downarrow \cdot N_R^\uparrow}}{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} + \sqrt{N_L^\downarrow \cdot N_R^\uparrow}}, (1)$$

where P_b is the beam polarization from CNI and jet polarimeter analysis, $\sigma^\uparrow(\sigma^\downarrow)$ is the single muon production cross section from crossings with polarized bunch spin up(down), $N^\uparrow(N^\downarrow)$ is the particle yield.

The measured A_N^{Incl} is corrected for the contribution of background by using

$$A_N^{Phys} = \frac{A_N^{incl} - r \cdot A_N^{BG}}{1 - r}, (2)$$

$$\delta A_N^{Phys} = \frac{\sqrt{(\delta A_N^{incl})^2 + r^2 \cdot (\delta A_N^{BG})^2}}{1 - r}, (3)$$

where $r = N^{BG}/N^{Incl}$ is the background fraction, and A_N^{BG} is the background asymmetry.

At RHIC energy, transverse single spin asymmetry in open charm production was suggested to probe gluon Sivers function[2] and the trigluon correlation functions in the nucleon[3]. The first measurement of A_N of single muons from open heavy flavor decay has been made as a function of x_F (Figure 1), and p_T in the forward and backward rapidities (Figure 2). The large uncertainty of background contribution dominates the systematic uncertainty. A direct comparison between the prediction for D mesons and muons from open heavy flavor (open charm and beauty) decay will be available soon. The observed asymmetries in single muon production are significantly smaller than the model prediction for D mesons with maximal gluon Sivers function in the same kinematics region (x_F and p_T) given in ref.[2].
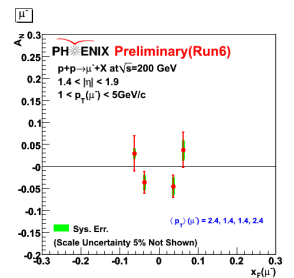
Fig. 1. A_N vs. x_F in single muon production.
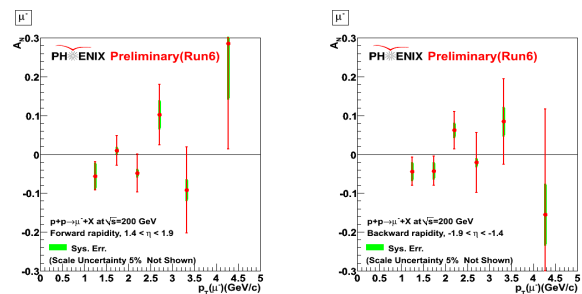
Fig. 2. A_N vs. p_T in single muon production in the forward (left) and backward (right) rapidities.

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Reaction Plane Dependence of Neutral Pion Production at $\sqrt{s_{NN}}$ =200 GeV Au+Au Collisions at RHIC-PHENIX

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[relativistic heavy ion collisions, jet quenching, elliptic flow]

It has been observed in central Au+Au collisions at Relativistic Heavy Ion Collider (RHIC) that the yield of neutral pion at high transverse momentum (p_T>5 GeV/c) is strongly suppressed compared to the one expected from $p + p$ collisions scaled by the number of binary collisions. This suppression is considered to be due to the energy lost by hard scattered partons in the medium (jet quenching), which results in a decrease of the yield at a given p_T. Many theoretical models have been proposed to understand the parton energy loss mechanism. One of which is GLV method[1] and it is one of the calculations that predicts that the magnitude of energy loss is proportional to square of the path length. Studying the path length dependence of energy loss should help in understanding of energy loss process.

Recently theoretical models (ASW[2], HT[3] and AMY[4]) to describe parton energy loss mechanism which involve the time-evolution of the medium produced at RHIC have been proposed. These models succeeded in reproducing the centrality dependence of $R_{AA}(p_T)$[5]. Figure 1 shows the nuclear modification factor, $R_{AA}(5<p_T<8$ GeV/$c)$ as a function of azimuthal angle and the $p_T = 15$ GeV/c of the ASW model curve which has largest variation in the above models. As shown in Fig. 1, even if we compare the curve with the $p_T = 15$ GeV/c of the ASW model to data at much lower p_T ($5<p_T <8$ GeV/c), these models are still unable to reproduce the azimuthal angle dependence of R_{AA},

Reaction plane detector was installed in RHIC-Year 2007 and reaction plane determination precision has been improved by a factor of two as compared to that in RHIC-Year 2004. Figure. 2 shows $v_2(\pi^0)$ as a function of p_T for each 20 % centrality bin. The only two high p_T points above 10 GeV/c are measured with full statistics. Measured $v_2(\pi^0)$ values are non-zero for all centrality bins. Two assumed functions are fitted to this data to understand the trend at high p_T. One is linear function ($f(v_2) = a \cdot p_T + b$) and the other is constant value ($f(v_2) = c$), where a, b and c are free parameters. At centrality bin range of 0-20 %, values of χ^2/NDF for constant and linear function are 4.45/5 and 4.34/4, respectively. At centrality bin range of 20-40 %, values of χ^2/NDF for constant and linear function are 4.39/5 and 1.49/4, respectively.

At centrality bin range of 40-60 %, values of χ^2/NDF for constant and linear function are 2.23/5 and 2.21/4, respectively. These results indicate that the values of $v_2(\pi^0)$ at most central and peripheral collisions tend to be constant while in mid-central collisions tend to decrease.

With the new data we will be able to measure the dependence of R_{AA} on azimuthal angle up to higher transverse momenta than ever before. We can also estimate the path length by measuring the azimuthal angle from reaction plane and mapping it into the shape of the participant region, which can be calculated by Glauber model for each impact parameter (centrality).
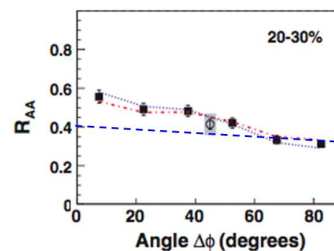
Fig. 1. $R_{AA}(5<p_T<8$ GeV/$c)$ as a function of azimuthal angle at centrality 20-30% and blue dashed line is ASW model curve at $p_T = 15$ GeV/c.
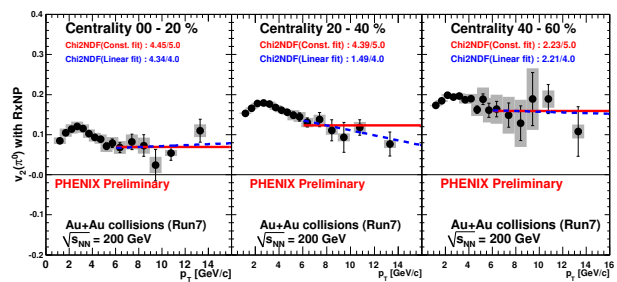
Fig. 2. $v_2(\pi^0)$ as a function of p_T for each 20 % centrality bin. Red solid and blue dashed lines show constant and linear function, respectively. Red and blue lines are fitted to data from 6 GeV/c.

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A study of ω meson production
in $\sqrt{s}_{NN}$=200GeV A+A collisions at PHENIX

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The measurement of hadrons under extreme conditions created by relativistic heavy-ion collisions is an intriguing study being carried out as part of the quest to observe the QCD phase transition, quark gluon plasma (QGP). PHENIX has provided systematic measurement of hadrons in Au+Au collisions suggesting that all meson production is suppressed due to jet quenching which is considered to be an effect of QGP[1] (Fig. 1 shows the nuclear modification factor of various particles; if there is no nuclear matter effect, the factor should be 1). Here, we contribute a measurement of ω mesons (782GeV/c^2) via the radiative decay mode ($\omega \to \pi^0\gamma$, $\pi^0 \to 2\gamma$) in $\sqrt{s}_{NN}$=200GeV Au+Au collisions. It has been found that nuclear modification of ω and ϕ may be showing interesting behaviors, and this may be the onset of a dependence of quark energy loss on flavor and/or spin.

To support the study of ω mesons in heavy-ion collisions, we have conducted an analysis of Cu+Cu collisions in $\sqrt{s}_{NN}$=200GeV. Since Cu+Cu collisions have lower multiplicity than Au+Au collisions and have different initial conditions, systematic measurement in this collision mode provide an important reference.

In addition to miminum bias (MB) trigger data, we used photon/electron trigger (ERT) data fulfilling high trigger condition of EMCal and RHIC, which are enriched with high-momentum photons to achieve better statistics for high momentum. The main challenge of this analysis is to handle the huge combinatorial background necessary for reconstructing particles from the three-body decay mode. We introduce the same kinematical cuts such as momentum and energy range that are used for Au+Au analysis to establish the high $S/\sqrt{B}$. Fig. 2 shows an example of an invariant spectrum reconstructed by 3 gammas after subtracting two types of background: one is the combinatorial background reconstructed by the mixed event method and the other is from a resonance such as $K_s^0(K_s^0 \to 2\pi^0)$. Even though the statistics are limited, we can see the peak of $\omega \to 3\gamma$ decays.
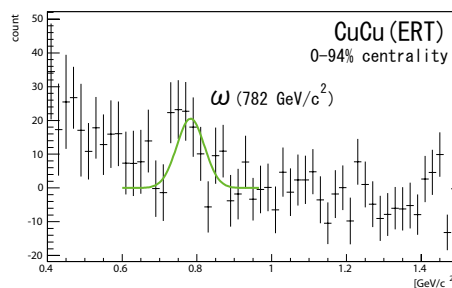
Fig. 2. Invariant Mass Spectra of 3γ (after subtracting backgrounds) at $6.5 < p_T(\omega) < 7.5$ [GeV/c] in ERT data set.

To evaluate the reconstructed efficiency, we performed a single ω event simulation using event generators based on Monte Carlo codes. The PHENIX implementation of the GEANT-based simulation and the event particle tracking software system, PISA were used to consider the detector response. Trigger efficiency of ERT is estimated from a comparison of single γ energy spectra between the MB and ERT data set.

The analysis of ω meson invariant yield in Cu+Cu is reaching the final stage. The behavior in R_{AA}, which is yet to be shown, is of great interest. We plan to publish the results of inclusive ω meson measurement including the Cu+Cu results together with the Au+Au results shown in Fig.1. Although considerable statistical errors are unavoidable, a comparison between these analyses is quite meaningful for seeing the effect of different initial conditions provided by different beam species.

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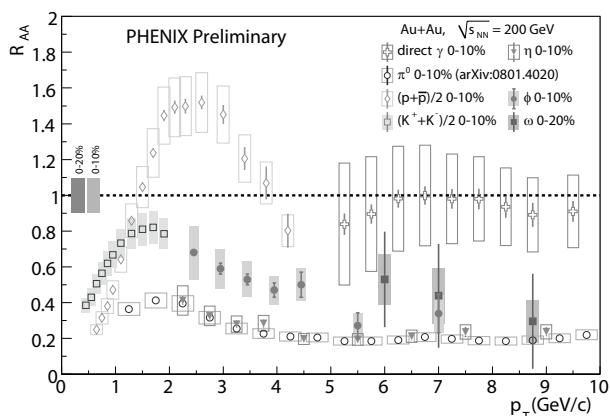
Fig. 1. Nuclear modification factor, R_{AA}, of various particles in central Au+Au collisions;[2] if there is no nuclear matter effect, the factor should be 1.

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High p_T Charged Pion Cross Section, Using PHENIX Central Arms[†]

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[Nuclear structure, charged pions, cross sections, proton proton collisions]

1 Introduction

Inclusive $\pi^{\pm}$ cross sections at high transverse momentum (p_T) are of interest as these can be used to confirm that pQCD is an applicable framework to study spin assymetries. Charged pion double helicity asymmetries from the 2006 run have been reported and compared with the latest theoretical predictions[3], which make use of fragmentation functions for charged separated species[2]. These asymmetry data will be useful in solving the puzzle of the origin of the proton's spin. In this report, we summarize the on-going effort to extract the charged separated pion cross sections for $5 < p_T < 10$ GeV/c.

2 PHENIX Detection of high pT $\pi^{\pm}$

High p_T $\pi^{\pm}$ which are to be used for a cross section measurement, are selected from the reconstructed high quality charged tracks in the drift chamber(DC). Minimum bias triggered data is used. The $\pi^{\pm}$ selection starts with applying an initial Čerenkov light emision threshold for the pions in the ring imaging Čerenkov detector (RICH)[1]. The reconstructed DC tracks are projected to the pad chambers (PC) and to the electromagnetic calorimeter (EMCal). The obtained hits in these detectors are compared to the actual associated hits. The standard deviations of the projected to the actual positions are evaluated as a function of momentum and incident angle; application of further cuts on these variables is known as pion track matching.

The main background for this analysis comes from secondary $e^{\pm}$ from γ conversions, which occur far from the collision vertex. These particles will produce light in the RICH with high efficiency and will mimic high pT $\pi^{\pm}$,, albeit with very low energy. The primary $e^{\pm}$ to $\pi^{\pm}$, ratios are 10^{-3}, thus $e^{\pm}$ coming from the vertex pose small contamination.

3 Montecarlo Studies Compared to Data

The light emitting thresholds in the RICH are as follows: $e^{\pm}$ 17MeV/c, $\pi^{\pm}$ 4.7GeV/c, $K^{\pm}$ 16 Gev/c, $p, \overline{p}$ 30 GeV/c. Within a p_T of 5-10 GeV/c, only $e^{\pm}$ and $\pi^{\pm}$ will emit Čerenkov light. The RICH has different efficiencies for $e^{\pm}$ and $\pi^{\pm}$ as the opening angle is different for each species. $e^{\pm}$ with their larger opening angle, will have recognizable ring or corona shaped light emission, while $\pi^{\pm}$ will emit light over a disk.

Fig. 1 shows the typical turn on threshold behaviour for a $\pi^{\pm}$. Several monte carlo studies have been initiated, some which are omitted in this report due to page limitations. One such study shows that most $e^{\pm}$ proceeding from γ conversions can be removed by applying a matching cut of 2.5 σ: from roughly 8,000 simulated conversion $e^{\pm}$ that mimic a high pT $\pi^{\pm}$, only about 72 will survive $\pi^{\pm}$, matching cuts. Zed, the z-coordinate at which the charged track crosses the drift chamber detector's reference radius (220 cm) is also studied. Conversion background has a strong zed dependance. $\pi^{\pm}$, have a flat zed ditribution, while conversion $e^{\pm}$, will typically show high tails at high zed. [Fig. 2] A cut on this z coordinate, is also an effective way of removing background.
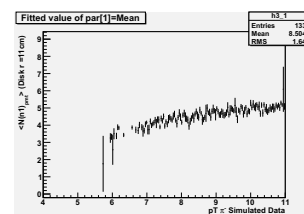
Fig. 1: Number of RICH photo multiplier tubes fired within a disk of 11 cm radius. The abcissa is the p_T of a simulated π^-
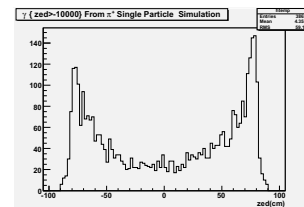
Fig. 2: Typical zed distribution of conversion $e^{\pm}$ proceeding from γ conversions, note the high tails.

4 Conclusions

The studies reported represent a small sample of the ongoing effort to measure charged pion cross sections at high p_T in the PHENIX detector. RHIC p+p data from the year 2006 is used in this analysis.

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Multiplicity Measurement in the Proton-Proton Collisions at the LHC†

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[Multiplicity, Color Glass Condensate (CGC), LHC]

Quantum Chromodynamics (QCD) predicts the color glass condensate (CGC) which is the consequence of the self interaction of the gluon[1)2)]. The hot and dense matter made at the Relativistic Heavy Ion Collider (RHIC) has the large elliptic flow in non-central Au+Au collision[3)], and the values of v_2, anisotropy for the azimuthal angle distribution of generated particles, agree with the results in the calculation of the hydrodynamics of the ideal fluid, but not with the model including the effect of CGC[4)]. In order to research for the hydrodynamical property of the high energy matter, the investigation of the effect of the CGC is needed.

The parton saturation as a consequence of CGC will be more conspicuous in the LHC than the RHIC. In the first collision of proton-proton at the LHC, which will be done at 2009, the effect of CGC will be found in the multiplicity measurement[5)]. In this report, the status of the preparation for the measurement of $dN/d\eta$ distribution of the charged multiplicity is described.

As the first step for the measurement of $dN/d\eta$, the estimation of the acceptance of the TPC for the charged particles was begun. These values are determined by the comparison of the input data from the event generator (MC event) to the event summary data (ESD) of the detector simulation and reconstruction. Data used to this analysis is Physics Data Challenge 2008 (PDC_08), which simulates the p+p collisions at $\sqrt{s} = 10$ TeV generated with Pythia 6 as the first physics for the LHC. The acceptance is assumed to be the function of pseudo-rapidity, vertex z position for the each track, and transverse momentum. $dN/d\eta$ is calculated as

$$\frac{dN}{d\eta}|_{\eta=\eta'} = \int_{Vz_1}^{Vz_2} \int_{p_T1}^{p_T2} \sum_{event} \sum_{track} C(\eta', z, p_T)$$
$$\times \left(\frac{dN}{dzdp_Td\eta}\right)_{\text{ESD}} dp_T dz \times C_{p_T, vz\ cut}(\eta') \quad (1)$$

where the summation is executed for the measured tracks and used events, the integration is executed for the region passed the vertex and p_T cutoff. $C(\eta', z, p_T)$ is the correction factor obtained from the simulation as follows.

$$C(\eta, z, p_T) = \frac{N_{acc}(\eta, z, p_T)}{N_{gen}(\eta, z, p_T)} \quad (2)$$

$N_{acc}(\eta, z, p_T)$ and $N_{acc}(\eta, z, p_T)$ are the number of

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charged particles accepted and generated, respectively. $C_{p_T, vzcut}(\eta')$ is the correction factor for the limited integration for p_T and the vertex z position. It is under development.

Calibration of the TPC using laser is also under development. The aim of the laser calibration is to measure the response of the TPC to the straight tracks at the known position. The distortion of the electric field at the edge of chambers, misalignment of the each sector, and the distortion of the drift velocity were measured. Figure 1 shows the distortion of the gain as a function of the distance from the edge of chambers of the TPC. The fit function shown in Fig 1 is used to the calibration code.
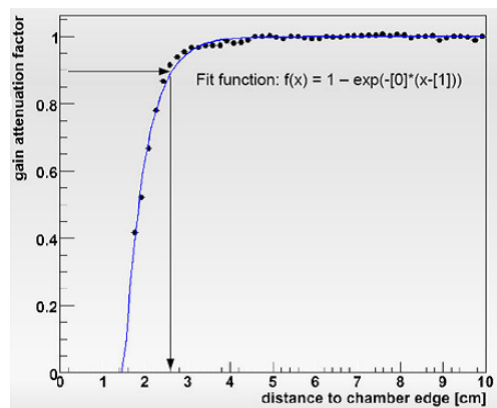
Fig. 1. The gain as a function of the distance from the edge of chambers of the TPC.

Estimation of the correction factor for the measurement of the charged multiplicity and the calibration of TPC will be developed until the first p+p collision at LHC scheduled on the September at 2009.

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Recent progress in precision pionic atom spectroscopy at RIBF[†]

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[hadron in medium, pionic atom, beam optics, spectroscopy]

1 Introduction

Spectroscopy of pionic atoms has been contributing to understanding of the origin of hadron masses[1]. According to theories, the hadron masses dynamically grow as chiral symmetry of the surrounding media, the vacuum, is partially broken[2]. The order of the symmetry breaking depends on the energy density of the vacuum and is parametrized by the magnitude of the quark condensate $< \bar{q}q >$[3,4]. At higher temperature or at higher density the quark condensate decreases and it becomes zero beyond certain limits.

The objective of the present experiment[5] and those to follow is evaluation of the magnitude of the quark condensate at the normal nuclear density through precise experimental determination of the in-medium isovector interaction strengths between the pion and the nucleus[5,6]. Previous results of pionic atom spectroscopy yielded first quantitative estimation of its reduction at the normal nuclear density to be about 33 % compared to that in the vacuum[1,7–10]. This estimation is consistent with the theoretical prediction of about 30 %, and is supporting the theories. However, the value of 33 % definitely needs more careful and precise evaluation.

In the present experiment, we are going to measure missing mass of the ^{122}Sn$(d,{}^{3}$He$)$ reaction near the pion emission threshold using the BigRIPS[11] in the RIBF[12] as a spectropmeter and to determine the binding energies and widths of the $1s$ and $2s$ pionic ^{121}Sn. Accomplishment of this experiment will be a start point for systematic study of pionic atoms.

Here, we will briefly summarize the recent progress.

2 Beam optics

To achieve better precision, one of the most ciritical issues is the beam optics of the spectrometer BigRIPS. Since the momentum spread of the incident beam ($\Delta p/p$) is as large as 0.1 %, its contribution to the experimental resolution is huge and is estimated to be about ~ 1 MeV (FWHM), which is about 5 times larger than target value of 200 keV. Thus, to compensate for the momentum spread, we need to develop a dispersion matching beam optics between two sections; the beamline SRC–target and the spectrometer

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target–F5 focal plane.

The dispersion matching condition in our experiment is described as

$$b_{16}s_{11} + b_{26}s_{12} + s_{16}t_{66} = 0 \qquad (1)$$

with the transfer matrices

$$\begin{pmatrix} x_f \\ a_f \\ \delta_f \end{pmatrix} = STB \begin{pmatrix} x_0 \\ a_0 \\ \delta_0 \end{pmatrix}, \qquad (2)$$

where

$$S = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix}, B = \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{21} & b_{22} & b_{26} \\ 0 & 0 & 1 \end{pmatrix}$$

and T denotes $(d,{}^{3}$He$)$ reaction at the target with $t_{66} \sim 1.31$, which is attributed to the relation between incident and outgoing momenta in the kinematics.

The largest difficulty to build above dispersion matching beam optics resides in the fact that the SRC is sitting in the most upstream of the system as a large optical element. Therefore, we need to study in detail the optics of the SRC first.
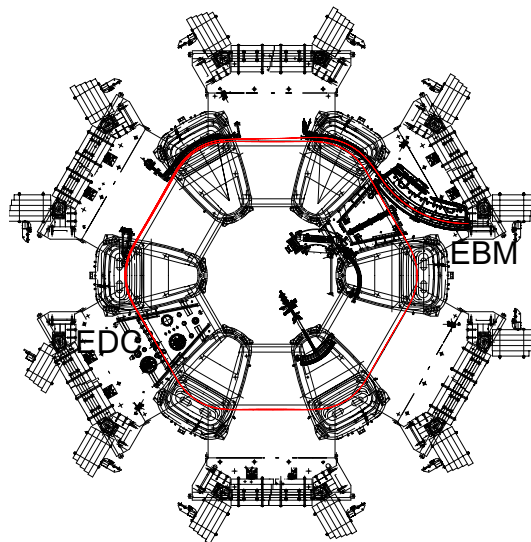
Fig. 1. Beam trajectories in the SRC.

We have performed a detailed calculation of the beam trajectories inside the SRC from EDC to EBM as shown in Fig. 1. At the EDC, the SRC is tuned to make an upright ellipsoid. Figure 1 shows the calculated beam trajectories in the SRC. Calculating the

derivatives of the trajectories, we have obtained the first order transfer matrix from EDC to EBM. Thus calculated matrix is

$$
\begin{pmatrix}
a_{11} & a_{12} & a_{16} \\
a_{21} & a_{22} & a_{26} \\
a_{61} & a_{62} & a_{66}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 & -0.34 & 7.69 \\
2.97 & -0.01 & -25.4 \\
0 & 0 & 1
\end{pmatrix}
$$

The beamline optics between EBM and the target is calculated so as to decouple the optics near the intermediate focal plane after QDT11 to leave room for flexibility to adjust to the properties of the incident beam since we have little knowledge on them. The first quadrupole quartet is used for this purpose, and the quality of the adjustment is measured at the focus after the QDT11. The obtained matrix is

$$
\begin{pmatrix}
b_{11} & b_{12} & b_{16} \\
b_{21} & b_{22} & b_{26} \\
b_{61} & b_{62} & b_{66}
\end{pmatrix}
=
\begin{pmatrix}
-0.39 & 0 & 4.60 \\
-2.90 & -2.58 & 21.0 \\
0 & 0 & 1
\end{pmatrix}
$$

The calculated beam optics for the beamline is shown in Fig. 2
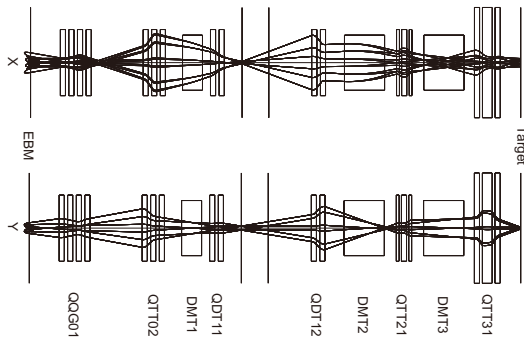
Fig. 2. Beam line optics from the SRC to the target.

The above obtained matrix is used for the optics calculation in the BigRIPS to fulfull Eq. 1

We are going to make a detailed test of the calculated beam optics in May, 2009.

3 Expected resolution

Based on the calculated beam optics, we have estimated the expected experimental resolution in FWHM depending on the emittance of the incident beam as shown in Fig. 3. The estimation is assuming the target thickness of 15 mg/cm^2, which contributes about 140 keV [FWHM].

As shown in Fig. 3, the emittance of the incident beam is crucial in the present spectroscopy and we need to optimize the horizontal beam size at EBM.

Fig. 3. Experimental resolution in FWHM depending on the horizontal beam size in σ at the EBM.

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4. Hadron Physics(Theory)

Glueball Decay in Holographic QCD[†]

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[Glueballs, Hadron physics, Superstring theory]

Glueballs, as excitations of gauge-invariant composite operators in Yang-Mills theories, remain illusive. Although the existence of the glueballs (of various types, such as scalar glueballs and tensor glueballs) is expected, their experimental identification in the hadron spectra remains difficult. This difficulty is largely due to the inability to compute reliably couplings of glueballs to ordinary mesons in strongly coupled QCD. Lattice QCD predicts for the mass of the lightest scalar glueball to be around 1600-1700 MeV, but it doesn't yet provide information on the glueball couplings and decay products/widths, which are indispensable for their identification. The Large Hadron Collider (LHC) will likely yield a huge amount of hadronic data, which can lead to progress in revealing the mystery of glueballs.

In this paper, using holographic QCD based on D4-branes and D8-anti-D8-branes,[1] we have computed couplings of glueballs to light mesons. We describe glueball decay by explicitly calculating its decay widths and branching ratios. Interestingly, while glueballs remain less well understood both theoretically and experimentally, our results are found to be consistent with the experimental data for the scalar glueball candidate $f_0(1500)$. More generally, holographic QCD predicts that decay of any glueball to $4\pi_0$ is surpressed, and that mixing of the lightest glueball with $q\bar{q}$ mesons is small.

The AdS/CFT (gauge/gravity) correspondence (duality) is one of the most important developments in string theory, and, holographic QCD refers to the application of AdS/CFT to QCD studies. The basic claim of the AdS/CFT correspondence is that correlation functions of gauge-invariant composite operators in large N_c gauge theories at strong 't Hooft coupling correspond to classical gravitational computations in higher dimensional gravity theories in curved backgrounds. The correspondence has been applied to (i) computation of glueball spectrum in large N_c pure Yang-Mills theory and to (ii) $q\bar{q}$ meson spectra/dynamics in large N_c QCD, which we review briefly below. These efforts have been quite successful in reproducing lattice and experimental data of hadrons, even though the real QCD is recovered in the "CFT" side only when one incorporates various corrections in the large N_c and large 't Hooft coupling expansion.

Here we combine these two efforts, (i) and (ii), in order to calculate couplings between the glueballs and the $q\bar{q}$ mesons, in the large N_c QCD.

The key merit of using holographic QCD is the fact that one not only can calculate the hadron spectra, but also can compute explicitly their *couplings*. It provides a more powerful method for constraining these couplings than the chiral perturbation technique. In particular, since glueballs are expected to be heavier than 1 GeV, derivative expansion in chiral perturbation becomes unreliable. Furthermore, current lattice calculations are not well suited for computing dynamical quantities such as decays and couplings. Our paper represents a first principle calculation for glueball decays, though in the approximation where the holographic duality is valid.

We compute the couplings between the glueballs and the $q\bar{q}$ mesons in this setting. In the dual description through the AdS/CFT, they correspond to the supergravity fluctuations and the Yang-Mills fluctuations on the D8-branes, respectively. These two sectors are coupled in the combined system of supergravity plus D8-branes. We substitute the fluctuations (wave functions) of the supergravity fields (corresponding to the glueball) and the D8-brane massless fields (mesons) into the D8-brane action and integrate over the extra dimensions, to obtain the desired couplings. Combining sectors (i) and (ii) is important not only due to its phenomenological impact but also because this represents the first computation in holographic QCD of the couplings between the supergravity fluctuations and the fields on the probe D-branes.

Once the couplings are obtained, we can compute the decay widths for various decay channels of a glueball, and study its possible mixings. Because the whole $q\bar{q}$ meson sector is combined into the D8-brane action, which is a higher-dimensional Yang-Mills lagrangian, several interesting mesonic features follow. For example, at the leading order (in the expansion of the large 't Hooft coupling), glueball decay to $4\pi_0$ is prohibited. There is no direct $4\pi_0$ coupling to the glueball, and, furthermore, glueball - ρ meson coupling also does not allow the $4\pi_0$ decay mode. As for the mixing, we can show that the lightest glueball has no mixing with $q\bar{q}$ mesons at the leading order of our expansion. These are our main predictions based on the holographic QCD.

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Quark Mass Deformation of Holographic Massless QCD[†]

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[Quark mass, Hadron physics, Superstring theory]

AdS/CFT correspondence, gauge/gravity duality, has provided us with a new avenue to compute observables in strongly interacting gauge theories via weakly coupled gravitational descriptions. Recently in superstring theory, using particular kinds of D-branes, there proposed a holographic model of QCD by Sakai and Sugimoto[1]), where the non-Abelian chiral symmetry and its spontaneous breaking is geometrically realized via a D4/D8/$\overline{\text{D8}}$ configuration. The model predictions for the meson spectrum and the couplings between them compare well with experiments with a good accuracy. Baryons in this model were also investigated. Moreover, this holographic model has an ability of predicting possible glue-ball interactions to mesons. There are many other QCD observables that have been analyzed in this model, which show that the model is a good approximation to real QCD at least in low energy, large N_c-limit.

Despite its success in many aspects, this model has an apparent shortcoming that the pions are massless. This is because the quarks are massless from the construction. In our work, we propose deformations of the Sakai-Sugimoto model which correspond to the introduction of the quark mass. Our deformations have additional D-branes away from the original confining N_c D4-branes, which still have a reasonable field theory interpretation. The original Sakai-Sugimoto model is restored once these additional D-branes are moved to spatial infinity in the bulk. In the field theory view-point, our idea is rather similar to the extended technicolor model, where we have an additional sector to the original QCD, which contains new techni-quarks interacting via new technicolor interactions. The quarks/techni-quarks are massless at UV, but the chiral symmetry (the electroweak symmetry in this case) is spontaneously broken by a techni-quark condensate driven by the strong technicolor gauge interactions. QCD quarks get explicit bare mass term from the techni-quark condensate, through quark-techniquark interaction.

To realize this idea in our set-up, we introduce additional N' D4-branes (we call them D4'-branes) which are parallel to, but separated from the original N_c D4-branes of QCD gauge symmetry. The total gauge symmetry is $SU(N_c + N')$ when the D4'-branes are on top of the original D4-branes, and it is broken to $SU(N_c) \times SU(N')$ by a Higgs mechanism via separating the D4' from the D4. Massive off-diagonal gauge bosons appear as strings suspended between the D4 and the D4'. We add N_f D8/$\overline{\text{D8}}$-branes as in Sakai-Sugimoto model to introduce massless quarks and techni-quarks, which are charged under the chiral symmetry $U(N_f) \times U(N_f)$. By assuming a strong technicolor $SU(N')$ dynamics on the D4'-branes, which replaces the D4'-branes with the Witten's geometry, the chiral symmetry is spontaneously broken by adjoining the D8/$\overline{\text{D8}}$-branes there, as in the Sakai-Sugimoto model but with the technicolor instead of the QCD gauge group. This breaking will be mediated to the QCD sector of the N_c D4-branes by, for example, the massive gauge bosons coming from the open strings stretched between the D4 and the D4'-branes. This induces the bare masses for the QCD quarks.

From the Feynman graphs that would induce quark masses from a techni-quark condensate, we can easily identify the corresponding string worldsheets that mediate this phenomenon in our D-brane configuration in flat space. We consider a circle following D4-D8-D4'-$\overline{\text{D8}}$-branes and a disk *worldsheet instanton* whose boundary is ending on this circle. It is responsible for the extended technicolor interactions coupling the quarks to the techni-quarks. Then we consider the strongly coupled field theory, or equivalently a weakly coupled gravity description, where we can identify the worldsheet instanton which has been responsible for the quark mass term. In the gravity description, where both D4 and D4'-branes are replaced by a near horizon geometry of a multi-center gravity solution, we have a closed loop on the surface of the probe D8-branes only, since the D8- and the $\overline{\text{D8}}$-branes are smoothly connected at two throats created by the D4- and the D4'-brane geometry. The previous worldsheet instanton in the weak coupling picture is now ending on this closed loop. The worldsheet instanton is a leading order contribution to the effective action of the D8-branes, since it is a planar diagram with a single boundary in the large N gauge theory. We show that this worldsheet instanton amplitude indeed induces the lowest mass perturbation for pions that is expected in the standard low energy chiral Lagrangian. We also show that the GOR relation is satisfied.

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Phenomenology of small x physics.

A. M. Stasto[*1,*2,*3]

Unitarity in Hadron collisions[a]

The LHC machine will open a new kinematical regime for studying strong interactions in the hadronic collisions. Of particular interest is the contribution to the cross section from semihard jets. The perturbative QCD formula for minijet production consitutes an important ingredient in models describing the total cross section and multiparticle production in hadron-hadron scattering at high energies. Using arguments based on s-channel unitarity we set bounds on the minimum value of p_T for which the leading twist minijet formula can be used. For large impact parameters where correlations between partons appear to be small we found that the minimum value of p_T should be greater than 2.5 GeV for LHC energies and greater than 3.5 GeV for cosmic ray energies of about 50 TeV. We also argued that for collisions with values of impact parameters typical for heavy particle production the values of minimum p_T are likely to be considerably larger. We also analyzed and quantified the potential role of saturation effects in the gluon density. We found that although saturation effects alone are not sufficient to restore unitarity, they are likely to play an important role at LHC energies.

Resummation at low x and strong coupling[b]

In recent years there has been large theoretical activity related to the duality between the string model in the anti de Sitter space and the conformal field theories. This duality offers a unique insight into the regime of the strong coupling constant in the gauge theory where standard perturbative methods fail. In particular case of the high energy scattering between the two hadrons the leading exchange is that of the Pomeron, a Regge trajectory with the quantum numbers corresponding to the vacuum. It was demonstrated that on the gravity side this scattering process is dominated by the exchange of the spin-two graviton. It is also known that the Pomeron in the perturbative theory can be computed using Feynman diagram technique, and it corresponds to the composite state of two reggeized gluons. It can be obtained as a solution to the evolution equation for the gluon Greens function at small values of Bjorken x. We have demonstrated that a particular resummation model for this evolution kernel for the gluon density at small x creates a bridge between the weak and strong couplings. The resummation model embodies both DGLAP and BFKL anomalous dimensions at leading logarithmic orders, as well as a kinematical constraint on the real emission part of the kernel. In the case of pure gluodynamics the strong coupling limit of the Pomeron intercept is consistent with the exchange of the spin-two, colorless particle.

Exact kinematics in the gluon cascades [c]

It is well known that the kinematic effects constitute a large portion of the higher order corrections to the kernels in the small x evolution equations for the parton densities. They are also present in the computation of the higher order anomalous dimensions of the standard renormalization group approach. The problem of kinematic effects in the gluon and color dipole cascades has been addressed in the large N_c limit of $SU(N_c)$ Yang–Mills theory. We investigated the tree level multi-gluon components of the gluon light cone wave functions in the light cone gauge keeping the exact kinematics of the gluon emissions. We focused on the components with all helicities identical to the helicity of the incoming gluon. The recurrence relations for the gluon wave functions were derived. In the case when the virtuality of the incoming gluon is neglected the exact form of the multi-gluon wave function has been obtained. Furthermore, we proposed an approximate scheme to treat the kinematic effects in the color dipole evolution kernel. The new kernel entangles longitudinal and transverse degrees of freedom and leads to a reduced diffusion in the impact parameter. When evaluated in the next-to-leading logarithmic (NLL) accuracy, the kernel reproduces the correct form of the double logarithmic terms of the dipole size ratios present in the exact NLL dipole kernel. Finally, we analyzed the scattering of the incoming gluon light cone components off a gluon target and the fragmentation of the scattered state into the final state. The equivalence of the resulting amplitudes and the maximally-helicity-violating amplitudes has been demonstrated in the special case when the target gluon is far in rapidity from the evolved gluon wave function.

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[a] Condensed from article[1].
[b] Condensed from article[2].
[c] Condensed from article[3].

An explanation of the NuTeV anomaly[†]

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[NUCLEAR PARTON DISTRIBUTIONS, Flavor dependence, Neutrino deep inelastic scattering]

The Paschos-Wolfenstein (PW) ratio is defined by[1]

$$R = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\overline{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\overline{\nu} A}},$$

where A represents the nuclear target, and NC (CC) indicates weak neutral current (charged current) interactions. This ratio was determined by the NuTeV collaboration in 2002[2] by using an iron target, where the measured inclusive deep inelastic (anti-) neutrino cross sections are integrated over the Bjorken scaling variable (x_A) and the energy transfer (y). The ratio can be expressed in terms of nuclear valence quark distributions $q_{A-} = q_A - \overline{q}_A$ by

$$R = \frac{g_v^u \langle x_A u_{A-} \rangle - g_v^d \langle x_A d_{A-} \rangle}{3 \langle x_A d_{A-} \rangle - \langle x_A u_{A-} \rangle} \equiv R_0 + \delta R$$

$$R_0 = \frac{1}{2} - \sin^2 \Theta_W$$

$$\delta R \simeq \left(1 - \frac{7}{3} \sin^2 \Theta_W \right) \frac{\langle x_A u_{A-} - x_A d_{A-} \rangle}{\langle x_A u_{A-} + x_A d_{A-} \rangle},$$

where Θ_W is the Weinberg angle, and for the quark weak vector charges (g_v^q) we follow the conventions of Ref.[3]. $\langle \ldots \rangle$ implies integration over x_A, therefore the quantities in angle brackets are the fractions of the target momentum carried by the valence u and d quarks. R_0 is the PW ratio for isospin symmetric matter, and is given solely in terms of the Weinberg angle.

If one can determine the correction term δR arising from the neutron excess, the PW ratio provides a unique way to measure the Weinberg angle. In the NuTeV analysis, this correction was determined by assuming that the target is composed of free nucleons. The result was[2] $R - \delta_f R = 0.2723$, which implies $\sin^2 \Theta_W = 0.2277$. The deviation from the Standard Model value (world average[4]) $\sin^2 \Theta_W = 0.2227$ is a three-sigma discrepancy [a], and was often considered as an indication of physics beyond the Standard Model.

In our previous work[5], we used the quark-diquark description of the nucleon in the Nambu-Jona-Lasinio model combined with the mean field approximation for infinite nuclear matter, to evaluate the valence quark distributions in isospin asymmetric nuclear environment. In this approach, which successfully describes the EMC effect[6], we found that the additional binding (symmetry energy) of u quarks in $N > Z$ matter leads to an enhancement of medium modifications of the u quark distributions, and as a result the EMC effect increases as Z/N decreases from 1 to 0.6. Here we use our in-medium quark distributions for the same neutron excess as in the NuTeV experiment (5.74%) to investigate the influence of these isovector medium modifications on the PW ratio.

We use the Standard Model value of $\sin^2 \Theta_W$, and split the correction into three pieces: $\delta R = \delta_f R + \delta_{\rm med} R + \delta_{\rm csb} R$. The naive ("free") and medium corrections are evaluated in our model, while the correction arising from charge symmetry breaking ($m_d > m_u$) is taken from Ref.[7]. Our results for $R - \delta_f R = R_0 + \delta_{\rm med} R + \delta_{\rm csb} R$ are shown in Table 1 in comparison to the NuTeV result quoted above. The medium

R_0	+ med	+ csb	NuTeV
0.2773	0.2741	0.2724	0.2723

Table 1. Results for the PW ratio after naive isoscalarity corrections.

correction $\delta_{\rm med} R = -0.0032$ comes mainly from the vector-isovector nuclear mean field (ρ^0), and only a small part from the Fermi motion of the nucleons. The final theoretical value, including medium modifications and charge symmetry breaking, is 0.2724, which explains the NuTeV result of 0.2723. Our conclusion is that the NuTeV measurement provides strong evidence that the nucleon is modified by the nuclear medium, and should not be interpreted as an indication for physics beyond the Standard Model.

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a) The result deduced by NuTeV is $\sin^2 \Theta_W = 0.2277 \pm 0.0013({\rm stat.}) \pm 0.0009({\rm syst.})$, while the world average is $\sin^2 \Theta_W = 0.2227 \pm 0.0004$.

EMC effect for parity-violating DIS[†]

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$$\left[\begin{array}{l}\text{NUCLEAR PARTON DISTRIBUTIONS, Flavor dependence, Parity violating deep inelastic}\\ \text{electron scattering}\end{array}\right]$$

In the deep inelastic scattering (DIS) of longitudinal polarized electrons on unpolarized nuclear targets (A), parity violating (PV) effects due to the interference between the photon exchange and Z^0 boson exchange lead to a non-zero spin asymmetry $A_{PV} = \dfrac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$. Here $\sigma_{R,L}$ denote the double differential cross sections for DIS of right and left-hand polarized electrons. In the Bjorken limit, we have[1]

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right].$$

Here x_A is the Bjorken variable of the nucleus multiplied by the mass number A, G_F is the Fermi coupling constant, and $y = \nu/E$ is the energy transfer divided by the incident electron energy. The term a_2 comes from the product of the electron weak axial current and the quark weak vector current, and is given by

$$a_2(x_A) = \frac{F_{2A}^{\gamma Z}(x_A)}{F_{2A}^{\gamma}(x_A)} = \frac{2\sum_q e_q\, g_v^q\, q_{A+}(x_A)}{\sum_q e_q^2\, q_{A+}(x_A)}.$$

Here $q_{A+}(x_A) = q_A(x_A) + \overline{q}_A(x_A)$ are the nuclear parton distributions, and for the definitions of the nuclear structure functions (F_{2A}^{γ} and $F_{2A}^{\gamma Z}$) and the quark weak vector couplings (g_v^q) we follow the conventions of Ref.[2]. The term a_3, which comes from the product of the electron weak vector current and the quark weak axial vector current, makes only a small contribution to the asymmetry, and will not be discussed here.

Because the structure functions $F_{2A}^{\gamma Z}$ and F_{2A}^{γ} have different flavor dependences, they will receive different medium modifications in isospin asymmetric nuclear systems ($N \neq Z$). This is clearly seen if we consider the isovector correction to first oder:

$$a_2(x_A) \simeq \left(\frac{9}{5} - 4\sin^2\Theta_W\right) - \frac{12}{25}\frac{u_{A+}(x_A) - d_{A+}(x_A)}{u_{A+}(x_A) + d_{A+}(x_A)},$$

where Θ_W is the Weinberg angle. It follows that a measurement of a_2 would give information on the flavor dependence of nuclear parton distributions. Conversely, if one can make reliable estimates of the isovector correction term, the spin asymmetry provides an independent method to determine the Weinberg angle.

Here we use the quark distributions in isospin asymmetric nuclear matter, calculated in our previous

work in the Nambu-Jona-Lasinio model[3], to show the isospin dependent medium modifications of the spin asymmetry term a_2. In Figs. 1 and 2, a_2^{naive} is the result without medium modifications (obtained by assuming that the target nucleus is composed of free nucleons), and a_2 is our full model result. The Standard Model value $\sin^2\Theta_W = 0.223$ is used. The results, which refer to the NJL model associated with a low energy scale, do not change much under Q^2 evolution in the valence quark region. We see that the medium modifications enhance the spin asymmetry for large x_A. The reason for this is that the isovector-vector mean field (ρ^0) leads to an additional binding of u quarks, which results in a softening of u_A compared to d_A in the valence quark region[3].
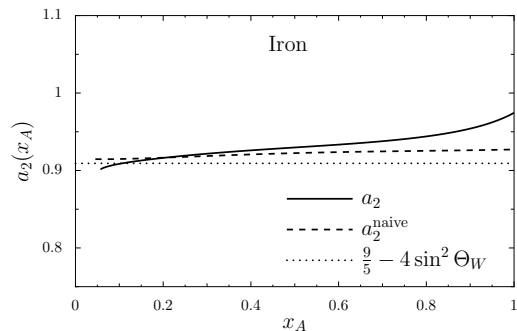
Fig. 1. Spin asymmetry a_1 for $Z/N = 26/30$.
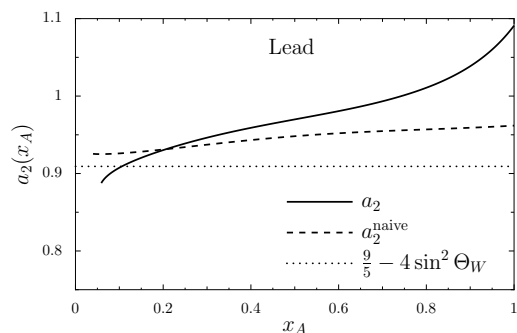
Fig. 2. Spin asymmetry for $Z/N = 82/126$.

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The study of multiquark states based on 1/Nc classifications

Toru Kojo [*1]

[Multiquark, $1/N_c$ expansion]

The hadron spectroscopy have provided a lot of clues to understand the dynamics of strong interaction, QCD. Nowadays, with concepts of color confinement and chiral symmetry breaking, the tendency of most hadrons, (conventional) mesons ($q\bar{q}$) and baryons (qqq), are well-classified by constituent quark picture. On the other hand, there exist exceptional hadrons as candidates of exotica, such as multiquark states with large number of quarks beyond two or three, meson-meson (baryon) molecules, and so on. Obviously we need new kinds of explanations, which would eventually unveil unexpected aspects of the theory. Fortunately recent experimental investigations provide an increasing number of data for exotica, e.g., pentaquark $\Theta^+(1530)$, exotic charmonia (X, Y, Z), $\Lambda(1405)$ as a candidate of meson-baryon molecule. Thus in the present situation, it may be possible to categorize exotica toward the construction of useful concepts for them in a similar way to using constituent quarks for conventional hadrons.

Among several candidates for exotica, in this work, we concentrate on the discussion of multiquark components, employing the σ meson ($I = 0$, $J^{PC} = 0^{++}$) as an example. The σ has almost all important ingredients as the exotica: not only usual $q\bar{q}$ (2q) component but hadronic states beyond the simple constituent quark picture such as glueball, $\pi\pi$ molecule, and $qq\bar{q}\bar{q}$ (4q) states. In this respect, the question always arising in theoretical studies of multiquark components is how to distinguish them from other hadronic states. To the best of our knowledge, there has been no simple and clearcut scheme to characterize the difference between them.

We try to solve this problem by introducing the classification scheme based on $1/N_c$ (N_c is number of color) expansion[1] for the hadronic states in the correlators made of quark gluon fields,

$$\Pi(q^2) = i \int d^4x e^{iqx} \langle T J_{4q}(x) J_{4q}^\dagger(0) \rangle \qquad (1)$$

where Π calculated in terms of quarks and gluons includes all possible hadronic states generated by 4q operator. In quark-gluon side, Π can be classified by $1/N_c$ as $\Pi = \Pi^{(0)} + \Pi^{(1)} + ...$, and they are related to the properties of hadronic states order by order in terms of $1/N_c$. For instance, we can show that some hadronic states can appear at the leading order of $1/N_c$, while other states can not[2].

In this scheme, even if we consider hadronic states

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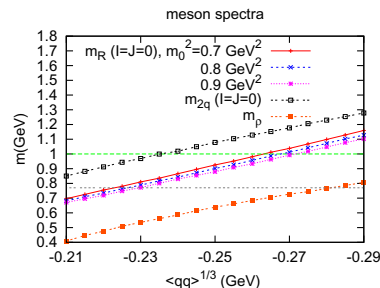
Fig. 1. The masses of 2q states in vector and scalar channel and 4q state as functions of quark condensate.

with the same quantum number, they can be distinguished by the choice of interpolating fields and by the order of $1/N_c$ in such correlation functions. Then we can identify whose contributions in quark-gluon dynamics are responsible to those from the hadronic states of our interest. After such an identification, we can verify that the mixing diagrams of these states are suppressed by higher order of $1/N_c$, and concentrate on the hadronic states without mixing effects.

We apply this scheme to the case of the σ meson. It turns out that the obstacles to extract 4q components from 4q correlators, i.e., the contributions of instanton, glueball, and, in particular, $\pi\pi$ scattering states can be identified and separated in terms of $1/N_c$, then we can concentrate on the remaining 2q and 4q contributions. The most remarkable point is that $1/N_c$ classification defines 4q states as the states which appear in 4q correlator but can not be obtained from the $\pi\pi$ scattering processes and 2q correlation functions. In this way, we can assign the hadronic states for proper quark-gluon diagrams in the computation[3].

After identification of quark-gluon graphs responsible to the 4q state, the actual computations of correlation functions in this work was done using QCD sum rule method. We calculate the masses of 2q states in the vector and scalar channels, and 4q state as function of quark condensate. The results in Fig.1 indicate that although 4q component can not explain the small empirical mass (~ 500 MeV) enough, still 4q configuration has smaller mass than 2q case by 150~200 MeV despite the larger number of quarks participating in the dynamics. This explicitly indicates the existence of the nontrivial correlation for the mass reduction of the 4q system.

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Non-Fermi-liquid magnetic susceptibility of quark matter[†]

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[Magnetic susceptibility, Non-Fermi-liquid effect, QCD phase diagram]

Nowadays the phase diagram of QCD has been extensively studied theoretically and experimentally. In particular, magnetic properties of QCD or its magnetic instablity is quite interesting, since it is related to the physics of compact stars, especially magnetars or primordial magnetic fields in the early universe. At high density but not high temperature, as expected in compact stars, the Fermi surface is a helpful concept. In recent papers, we have discussed the magnetic properties of quark matter by evaluating the magnetic susceptibility within Fermi-liquid theory. We have taken into account the anomalous self-energy for quarks due to the dynamic screening effect for the transverse gluons as well as the static screening effect given by the Debye mass for the longitudinal gluons.

In ref.1), we have studied the magnetic susceptibility at $T = 0$. We have seen that the transverse mode only receives the dynamic screening due to Landau damping, so that it still gives logarithmic singularities for the Landau-Migdal parameters, but that they cancel each other in the magnetic susceptibility to give a finite result. In refs. 2) and 3), we have also studied the magnetic susceptibility at finite temperature. The magnetic susceptibility at finite temperature is given by

$$
\begin{aligned}
&(\chi_M/\chi_{\text{Pauli}})^{-1} \\
&= 1 - \frac{C_f g^2}{12\pi^2 E_F k_F}\left[m(2E_F+m) - \frac{1}{2}(E_F^2 + 4E_F m - 2m^2)\kappa\ln\frac{2}{\kappa}\right] \\
&\quad + \frac{\pi^2}{6k_F^4}\left(2E_F^2 - m^2 + \frac{m^4}{E_F^2}\right)T^2 \\
&\quad + \frac{C_f g^2}{72}\frac{(2k_F^4 + k_F^2 m^2 + m^4)}{k_F^3 E_F^3}T^2\ln\left(\frac{\Lambda}{T}\right) + O(g^2 T^2). \quad (1)
\end{aligned}
$$

where χ_{Pauli} is the Pauli paramagnetism, $\chi_{\text{Pauli}} \equiv \bar{g}_D^2\mu_q^2 N_c k_F \mu/4\pi^2$, $C_f = (N_c^2 - 1)/2N_c$, and κ is defined by $\kappa = M_D^2/2k_F^2$ with the Debye mass M_D. Λ is a cut-off parameter and should be of $O(M_D)$.

The magnetic susceptibility at $T = 0$ is given by the first and second terms in Eq. (1). The $\kappa\ln\kappa$ term originates from the effective cut off of the longitudinal mode due to static screening. One can see that the magnetic susceptibility has $T^2\ln T$ dependence besides the usual T^2 dependence. This anomalous temperature dependence comes from the dynamic screening effect for the transverse gluons and is an interesting *non-Fermi-liquid effect* in the magnetic susceptibility. It corresponds to the well-known $T\ln T$ dependence in the specific heat[4]. The divergence of χ_M signals the magnetic instability of quark matter to the ferromagnetic phase. At low temperature, $\ln(\Lambda/T) > 0$ so that

the $T^2\ln T$ term gives positive contribution to χ_M^{-1}. Therefore, both T-dependent terms in Eq. (1) work against the magnetic instability. It may be interesting to note that the static screening gives the term proportional to $M_D^2\ln M_D^{-1}$, while the dynamic screening gives the $T^2\ln T^{-1}$ term; the Debye mass M_D works as an infrared (IR) cutoff to remove the infrared singularity in the quasi-particle interaction exchanging the longitudinal gluons, whereas, at finite temperature, temperature itself plays a role of the IR cutoff through the dynamic screening for the quasi-particle interaction.
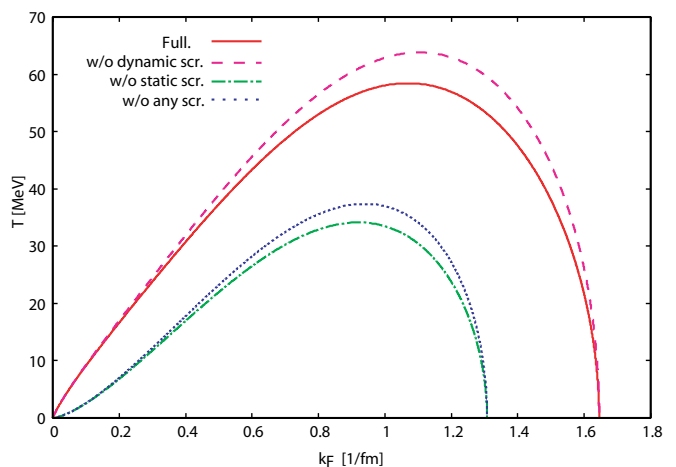
Fig. 1. Magnetic phase diagram in the density-temperature plane. The solid, dashed, dash-dotted, dotted curves show the results for the full expression Eq. (1), the one without the $T^2\ln T$ term, without the $\kappa\ln\kappa$ term, and without both of the $T^2\ln T$ and $\kappa\ln\kappa$ terms in Eq. (1).

We show a magnetic phase diagram of QCD on the density-temperature plane for $\alpha_s = 2.2$ and $m = 300\text{MeV}$ in Fig. 1. The four curves corresponds to the critical curves given by Eq. (1) under four different assumptions. The magnetic phase transition occurs on the critical curves: below the critical curves quark matter is in the ferromagnetic phase, while it is in the paramagnetic phase above them. One can see that static screening can enlarge the ferromagnetic region. As discussed in ref.1), it depends on the number of flavors whether the static screening works for ferromagnetism or not, which is peculiar to QCD. It also turns out that dynamic screening works against the magnetic instability and can reduce the ferromagnetic region in the phase diagram up to a point but this effect is not so large.

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Temperature dependence of quarkonium correlators

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Quarkonium properties at finite temperature received considerable interest since the famous conjecture by Matsui and Satz that color screening will lead to quarknonium dissociation, which in turn can signal the onset of deconfinement in heavy ion collisions[1]. This problem has been studied using potential models with screened temperature dependent potential[2]. In-medium quarkonium properties are encoded in the corresponding spectral functions which in turn are related to meson (current-current) correlation functions in Euclidean time. Euclidean correlation functions can be calculated on the lattice. Therefore one can hope to learn something about in-medium quarkonium properties by studying the temperature dependence of meson correlators on the lattice. In particular, attempts to reconstruct quarkonium spectral functions using the Maximum Entropy Method (MEM) were presented in Refs.[3–5]. The study of the spectral functions using MEM indicated that 1S charmonia may survive in the deconfined phase till temperatures as high as $(1.6 - 2.2)T_c$[3,4]. This result is closely related to the small temperature dependence of the Euclidean correlator in the pseudo-scalar channel[4,5]. On the other hand the large temperature dependence of the scalar and axial-vector correlators has been interpreted as evidence for the expected dissolution of the P-state charmonium. However, it has been pointed out that zero mode contribution, i.e. the contribution from the spectral functions at very small frequencies could lead to large temperature dependence of the Euclidean correlators[6,7]. Therefore in order to understand quarkonium properties at finite temperature and their relation to collective effects, e.g. screening it is important to get a detailed understanding of the temperature dependence of the Euclidean correlators, including the role of the zero mode contribution. Here I discuss the temperature dependence of quarkonium correlators calculated in quenched approximation on isotropic lattices.

Since the width of the transport peak is very small[6], the zero mode contribution is independent of the Euclidean time τ to a good approximation. Therefore the zero mode contribution will not show up in the derivative of the correlation functions. To check this I calculated the ratio of the derivatives $G''^i(\tau, T)/G_{rec}''^i(\tau, T)$, where the reference correlator (the so-called reconstructed correlator) is defined as

$$G_{rec}^i(\tau, T) = \int_0^\infty d\omega \sigma^i(\omega, T^*) \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}. \quad (1)$$

Here T^* is some reference temperature well below the

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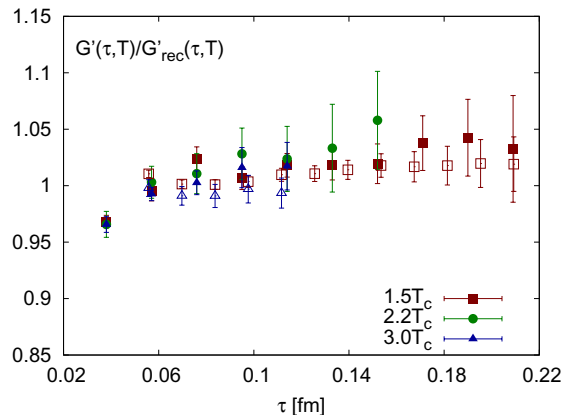
Fig. 1. The ratio of the derivatives $G'(\tau, T)/G_{rec}'(\tau, T)$ in axial-vector channel. The results from anisotropic lattice calculations[5] are also shown (open symbols).

transition temperature T_c. Furthermore, the index i denotes different channel (e.g. vector, pseudo-scalar etc.). The numerical results for this ratio in the axial-vector channel are shown in Figure 1. As one can see from the figure the ratio is temperature independent to a very approximation and is close to unity. This means that almost the entire temperature dependence of the axial-vector correlator in the Euclidean time is given by the zero mode contribution and the expected dissolution of P states is not reflected in the correlators. The figure also shows that similar temperature dependence is found in calculation with anisotropic lattices. The temperature dependence of the scalar correlator follows the same pattern as the axial-vector correlator. A closer analysis of the zero mode contribution shows that it can be well described by a quasi-particle model, where the heavy quark masses receive a small thermal correction[8]. The details of the analysis are presented in a recent publication[8].

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Heavy-quark bound states in an anisotropic hot QCD plasma[†]

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[Quarkonium, QCD, Plasma, Viscosity]

In Quantum Chromodynamics (QCD) with small t' Hooft coupling at short distances non-relativistic quarkonium states exist. At high temperatures, the deconfined phase of QCD exhibits screening of static color-electric fields which may lead to dissociation of quarkonium states. Inspired by the success at zero temperature, potential models have also been applied to understand quarkonium properties at finite temperature[1].

Here, we assess the properties of quarkonium states in a QCD plasma which exhibits an anisotropy of the particle momenta, $f(\vec{p}) = f_{\mathrm{iso}}(p) - \xi \frac{p_z^2}{2pT} f_{\mathrm{iso}}(p)(1 \pm f_{\mathrm{iso}}(p))$. This arises due to a locally anisotropic hydrodynamic expansion of a plasma with non-vanishing shear viscosity[2]: $\xi = (10/T\tau)\,\eta/s$, where ξ is the anisotropy parameter, T is the temperature, τ is proper time (and $1/\tau$ is the Hubble expansion rate), and η/s is the ratio of shear viscosity to entropy density.

We model the inter-quark potential in the deconfined phase as follows[3]:

$$V(r,T) = -\frac{\alpha}{r}\left(1 + m_D\, r\right)e^{-m_D r} + 2\frac{\sigma}{m_D}\left[1 - e^{-m_D r}\right] - \sigma r e^{-m_D r}. \quad (1)$$

Here, $\sigma = 0.223$ GeV^2 is the string tension and $m_D(T)$ is the Debye screening mass. Eq. (1) interpolates from the Cornell potential at short distance to an exponentially Debye-screened string attraction at large r. For an anisotropic plasma the Debye mass $m_D(T)$ is replaced by an angular dependent screening scale $\mu(\theta; \xi, T)$ which can be obtained from the "hard thermal loop" resummed gluon propagator appropriate for an anisotropic plasma[4]. The potential now depends not only on the distance between the Q and the $\overline{Q}$ but also on the angle θ between their separation and the direction of anisotropy.

The binding energies follow from the three-dimensional Schrödinger equation, see Fig. 1. They decrease with temperature T but increase with the anisotropy ξ. This is due to the fact that in an anisotropic plasma the screening scale $\mu(\theta)$ at a given temperature is smaller than the corresponding Debye mass $m_D(T)$, so screening is weaker.

Fig. 2 shows the binding energies of the $1P$ states of bottomonium. The anisotropy leads to a preferred

polarization of the χ_b, with about 50 MeV splitting between states with angular momentum $L_z = 0$ and $L_z = \pm 1$, respectively. The experimental confirmation of such a polarization at RHIC or LHC may provide first evidence for a non-zero viscosity of QCD near T_c.

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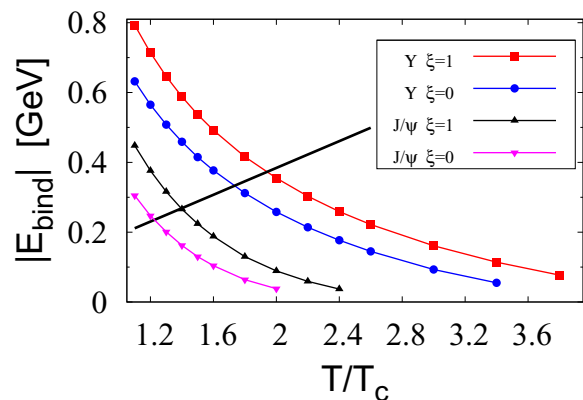
Fig. 1. Binding energies of the $1S$ states of charmonium and bottomonium for two values of the plasma anisotropy parameter ξ. The straight line corresponds to a binding energy equal to the temperature.
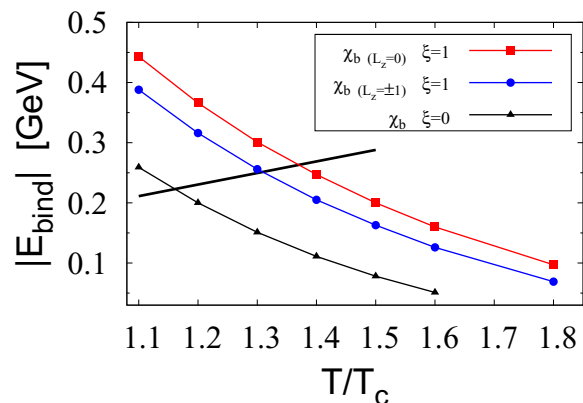
Fig. 2. $1P$ state of bottomonium.

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Improved non-perturbative renormalization in lattice QCD[†]

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Recent algorithmic developments and increasing power of supercomputers have made it possible to calculate basic physical quantities involving strong interaction from the first principles using lattice QCD with the light quark (u, d, s) degree of freedom consistently taken into account. It often is the case that the calculated quantity needs renormalization to remove the ultraviolet divergence and/or to match to a theory with higher energy scale such as the Weinberg-Salam theory of electroweak interaction. Renormalization can be done by perturbation theory in principle. However, the lattice perturbation theory poorly converges, thus should be avoided. Instead, a non-perturbative renormalization (NPR) on the lattice should be used.

The most practical non-perturbative renormalization program is provided by RI/MOM scheme[1], where the renormalization condition is imposed in a regularization independent way to the amputated off-shell forward Green function of external quark states with the operator insertion. The external momentum sets the renormalization scale $\mu^2 = p^2$. This scheme has successfully applied to many lattice calculations, including the recent domain wall fermion simulations[2].

Although by using the RI/MOM-scheme NPR the systematic uncertainty from the use of lattice perturbation theory is eliminated, there still is a problem, which has only been revealed by the use of state-of-the-art chiral fermion (domain wall fermion) calculations. It is an unwanted contamination of the non-perturbative effect, and becomes another source of the systematic error. The mechanism of how this contamination occurs is associated with the momentum configuration. Possible small momentum flow in the internal loop, for the particular momentum configuration conventionally employed, triggers the contamination. We have come up with a solution of this problem by changing the kinematics of the external momentum to the ones that do not involve exceptional momenta (which have zero partial sum), thus, reduces the small momentum flow.

The quark mass renormalization Z_m, calculated through bilinear operator renormalization of scalar or pseudoscalar, is one of the worst cases that suffer from the contamination. In the calculation using domain wall fermions the reported strange quark mass renormalized in $\overline{\text{MS}}$ scheme at $\mu = 2$ GeV read[3],

$$m_s^{\overline{\text{MS}}} = 107.3(4.4)_{\text{stat}}(4.9)_{\text{syst}}(9.7)_{\text{ren}}\text{MeV}. \quad (1)$$

The largest error is the third, which arises from the renormalization, where there are two dominant contributions: (i) aforementioned contamination of un-

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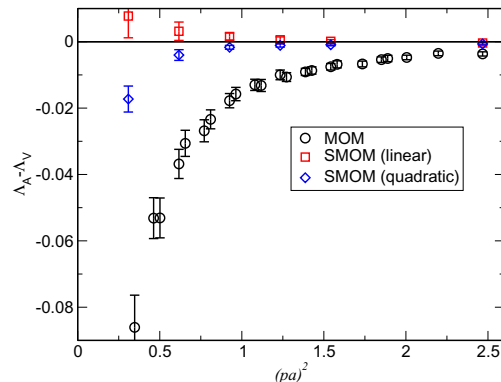
Fig. 1. Difference of axialvector and vector vertex function for the MOM and SMOM schemes. Chiral extrapolations with linear and quadratic in quark mass are shown for the SMOM scheme.

wanted non-perturbative effect. We estimate the corresponding uncertainty to be about 7%. (ii) The matching from the RI/MOM to the $\overline{\text{MS}}$ scheme. The perturbative series in continuum theory for this matching is known to 3-loops but converges very poorly. The uncertainty is estimated to be about 6%.

We have constructed a new scheme called RI/SMOM scheme[4][5] which makes use of non-exceptional momenta, thus is expected to reduce the systematic error from the contamination (i). We have performed a numerical test[5] and the result is promising. Figure 1 shows the difference of the vector and axial vector vertex amplitude as a function of the squared renormalization scale. The original MOM scheme shows difference due to spontaneous chiral symmetry breaking, sizable at low energy region. The same quantity in the new SMOM scheme is very small: the non-perturbative contamination got reduced as expected. After all the systematic error of Z_m from the contamination is get reduced to the level less than 3%. It also appears from the perturbative calculation[4] that the error (ii) shrinks a lot from the original scheme due to almost a factor 10 smaller one-loop correction. Thus, the new scheme is preferable by the two good reasons.

The concept of the new MOM scheme with non-exceptional momenta is quite general. It can be applied to other composite operators such as four quark operators for $K^0 - \overline{K^0}$ mixing and $K \to \pi\pi$ decays.

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(2+1)-flavor DWF QCD and chiral perturbation[†]

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[Quantum Chromodynamics, Hadron Physics]

Using QCDOC computers at RIKEN BNL Research Center, University of Edinburgh and Brookhaven National Laboratory, we performed a series of lattice quantum chromodynamics (QCD) calculations with two degenerate up and down quarks and one heavier strange quark fully dynamically represented by the domain-wall fermions (DWF) scheme[1]. The strange quark mass used turned out to be about 12 % heavier than the physical. The degenerate up and down mass were set to about 3/4, 1/2, 1/3 and 1/5 of the strange mass. The lattice cut off turned out to be about 1.7 GeV, and correspondingly the lattice spatial volume is about $(2.7\text{fm})^3$. These consist the most realistic set of lattice QCD numerical calculations ever performed.

The realistic strange mass and sufficiently light up and down mass aided by sufficiently large spatial volume allow detailed theoretical study of the role of flavor and chiral symmetries in hadron physics. We found the conventional SU(3) next-to-leading order (NLO) chiral perturbation theory (ChPT) that treats as if all three light quark flavors, strange, down, and up, have small mass compared to the chiral scale, fails. In other words we found the physical strange mass too heavy to be considered degenerate with the light up and down. This is an important discovery that calls into question many conventional analyses of hadronic phenomena that assumed the degeneracy of three light flavors. In contrast the SU(2) ChPT, that treat only the two lightest flavors of down and up degenerate, works.

In addition this work so far has resulted in three Phys. Rev. Letters publications: 1) a very accurate estimation of the kaon bag parameter[2], B_K, of the in-
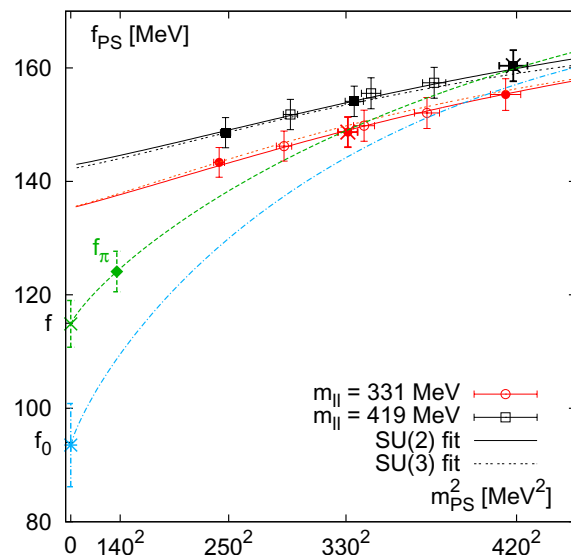
Fig. 1. SU(3) next-to-leading order (NLO) chiral perturbation theory (ChPT) fails, while SU(2) works: read ref.[1] for details, especially its Fig. 18. Physical strange quark mass is too heavy for NLO ChPT to work.

direct CP-violating mixing of neutral kaon, 2) another very accurate estimation of the K_{l3} form factor[3], and 3) an unexpectedly large finite-size effect on nucleon isovector axial charge[4,5], g_A. The first two results impact accurate quantitative determination of the CKM quark mixing matrix and thus the human endeavor in search of physics beyond the standard model. The third points out a difficulty that still stands in our way toward full understanding of hadronic physics. We are working on a series of lattice QCD ensembles at higher cutoff of about 2.4 GeV to improve on our understanding of this rich physics.

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Nucleon form factors in (2+1)-flavor dynamical DWF QCD[†]

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[Quantum Chromodynamics, Hadron Physics, Nucleon Structure]

The isovector form factors of nucleon are associated with the vector, $V_\mu^+ = \bar{u}\gamma_\mu d$, and axialvector, $A_\mu^+ = \bar{u}\gamma_\mu\gamma_5 d$, currents with up- and down-quark spinors u and d. Four form factors arise in matrix elements of these currents between proton and neutron states: the vector-current matrix element $\langle p|V_\mu^+(x)|n\rangle$ gives rise to the vector, F_V, and induced tensor, F_T, form factors,

$$\bar{u}_p\left[\gamma_\mu F_V(q^2) + \sigma_{\mu\lambda}q_\lambda F_T(q^2)\right]u_n e^{iq\cdot x}.$$

F_V is equivalent to F_1 and F_T to $F_2/(2M_N)$ in the isovector electromagnetic form factors. The axialvector-current matrix element, $\langle p|A_\mu^+(x)|n\rangle$, gives rise to the axialvector, F_A, and induced pseudoscalar, F_P, form factors,

$$\bar{u}_p\left[\gamma_\mu\gamma_5 F_A(q^2) + iq_\mu\gamma_5 F_P(q^2)\right]u_n e^{iq\cdot x}.$$

Here q denotes four-momentum transfer between the proton and neutron states. While the vector charge, $g_V = F_V(0)$, is not affected by the strong interaction because the vector current is conserved, the axial charge, $g_A = F_A(0)$, is affected: the ratio g_A/g_V deviates from unity, $1.2695(29)$[1]. Calculation of this ratio and the other form factors requires adequate treatise of flavor and chiral symmetries of quarks. Conventional lattice fermion schemes, however, have difficulty with them. In contrast the domain-wall fermions (DWF) method that we, RIKEN-BNL-Columbia (RBC) collaboration, pioneered works very well[2]. The RBC and UKQCD collaborations jointly generated state-of-the-art lattice QCD ensembles with "(2+1) flavors" of quarks. The strange mass is fixed at a realistic value about 12% heavier than the physical and degenerate up- and down-quark mass varies down to about 1/5 of this strange mass[3]. Using these we reported unexpectedly large finite-size effect on the g_A/g_V ratio[4].

In the present work we study the momentum-transfer dependence of all the four isovector form factors[5]. We found these form factors allow conventional dipole fitting and so extracting quantities such as anomalous magnetic moment or mean-squared charge radii. The signals and the dipole fits to them for conserved vector-current, F_V and F_T, are of very good
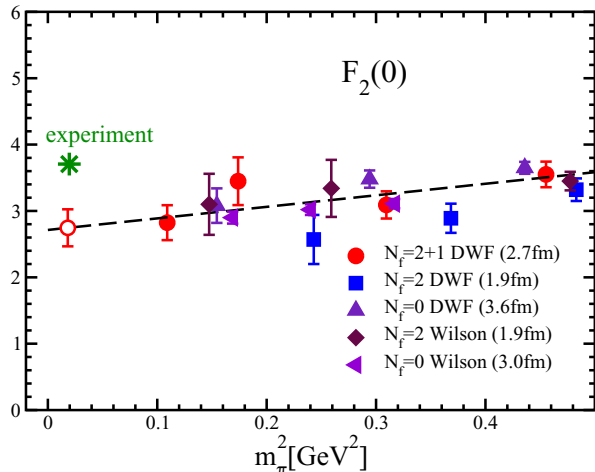
Fig. 1. Calculated isovector part of the nucleon anomalous magnetic moment compares well with the experiment.

quality: the extracted value of the anomalous magnetic moment, $F_2(0)$, as is shown in Figure 1, compares well with the experiment. The Dirac and Pauli mean-squared charge radii, however, significantly underestimate the corresponding experimental values. This can be explained by still too heavy up and down quark mass. Correspondingly we do not observe any logarithmic divergence toward the chiral limit that some models motivated by chiral perturbation predicts. The axialvector form factors, F_A and F_P, are of lesser statistical quality but provide us evidence that they suffer the same finite-size effect we observed in the axial charge, g_A[4]. Nevertheless we obtained good description of the Goldberger-Treiman relation. The extracted values for pion-nucleon coupling, $g_{\pi NN}$, and muon-capture coupling, g_P, also compare favorably with the experiments.

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Eta meson from two flavor dynamical domain wall fermions[†]

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[Quantum Chromodynamics, Hadron Physics]

We explore the spectrum of the flavor singlet pseudoscalar meson, η', in two-flavor ($N_f = 2$) lattice Quantum Chromo Dynamics (QCD). The continuum-like relation between the topology of the QCD vacuum and the $U(1)_A$ anomaly, which prevents the η' meson from being a Nambu-Goldstone boson, is expected to hold in the domain wall fermions (DWF) used as a lattice quark field in this calculation.

We employ the ensemble of $N_f = 2$ QCD vacuum[1] generated with DWF quark actions. The lattice size is $16^3 \times 32$, the lattice scale is $a^{-1} \approx 1.5$ GeV ($a \approx 0.13$ fm), and the residual chiral breaking $m_{\rm res} = 0.00137(4)$ which is about an order of magnitude smaller than the up/down quark masses used in the simulations, $m_f = 0.02 - 0.04$, which correspond to $m_\pi/m_\rho \approx 0.51$-0.64. The number of vacuum samples are about 500-1,000.

To reduce the large statistical uncertainties of the η' meson propagator, we introduce a smeared quark operator, q_S, which is a superposition of the local quark operator q_L at neighboring space-time in a gauge-covariant manner. The shape of q_S in terms of q_L is Gaussian with its width being set to enhance the overlap to the quark wavefunction in the ground state hadrons.

The η' propagator, projected to the zero spacial momentum, consists of the connected, $C_{\gamma_5}(t)$, and the disconnected quark loop, D_{γ_5}, contributions:

$$\int d^3x \langle \eta'(\vec{x},t)\eta'^\dagger(\vec{0},0)\rangle = C_{\gamma_5}(t) - N_f D_{\gamma_5}(t) .$$

Here the Hermitian operator of the η' meson, is constructed by the quark operators, $q_{I,f}$ and $\bar{q}_{J,f}$ as, $\eta'_I(\vec{x},t) = \frac{1}{\sqrt{N_f}} \sum_{f=1}^{N_f} \bar{q}_{I,f}(\vec{x},t)i\gamma_5 q_{I,f}(\vec{x},t)$, where $f = 1, ..., N_f$ is the flavor index, and I denotes whether we use the local quark field (L) or the smeared field (S), which controls the ground-state overlap. Both of the correlation functions, $C_{\gamma_5}(t)$ and $D_{\gamma_5}(t)$, are calculated using the complex random $\boldsymbol{Z}_2$ source.

The η' mass is extracted by fitting the propagator in following two ways, and the results are compared with each other to estimate systematic uncertainties: (A) Standard method: the propagator is fit to a single

m_f	$m_{\eta'}$	t_0	$t_{\min}$	$t_{\max}$	method
0.02	0.477(40)		2	5	(A)
	0.473(50)	2	$t_0 + 1$	6	(B)
0.03	0.571(60)		3	5	(A)
	0.600(44)	2	$t_0 + 1$	6	(B)
0.04	0.497(17)		2	5	(A)
	0.492(15)	2	$t_0 + 1$	5	(B)

Table 1. $am_{\eta'}$ for each simulation points.

exponential dumping function in time distance from the source, $C \cosh[m_{\eta'}(t - N_T/2)]$, by assuming only the ground state propagates. (B) Variational method: the mass of the first excited state m_{η^*} is also taken into account. Both the local ($I, J = L$) and the smeared ($I, J = S$) interpolation fields are used to construct 2×2 correlation functions $X_{IJ} \equiv \langle O_I O_J \rangle$ ($I, J = S, L$). Eigenvalues of the normalized correlation matrix are then fit as a function of t: $\lambda(t; t_0) = \frac{\cosh[m(t - N_T/2)]}{\cosh[m(t_0 - N_T/2)]}$ to obtain the masses of the states. t_0 is fixed to the point for the normalization.

The numerical values of $m_{\eta'}$ and time ranges used in their fits are given in Table 1 for both method (A) and (B). We did not use a propagator from longer distance, where the statistics are too poor and the standard error analysis would not be reliable, although the inclusion of a few more data points does not change the fitted results for most of the masses. Method (B) produces flatter plateaux than that in method (A).

Then the masses are extrapolated using either of

$$m_{\eta'} = B_0 + B_1(m_f + m_{\rm res}) \quad \text{(linear type),} \quad (1)$$
$$m_{\eta'}^2 = C_0 + C_1(m_f + m_{\rm res}) \quad \text{(AWTI type),} \quad (2)$$

to estimate the mass of η' at the physical quark mass point. Our main estimation for the mass of η' at the physical quark mass point is obtained from the variational method (B) and chiral extrapolation using the lowest order of ChPT (2):

$$m_{\eta'}^{\rm phys} = 819(127) \text{ MeV} , \quad (3)$$

which is close to the experimental value. One of the most obvious direction to remove various sources of the systematic errors in this first calculation using chiral quarks is to include the dynamical strange quark effect[3].

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5. Particle Physics

$O(\alpha_s a)$ matching in static heavy and DW light quark system[†]

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In the lattice QCD simulation, the Heavy Quark Effective Theory (HQET)[1] is widely used for treatment of the b quark. However, it has the following difficulties (and solutions).

i The static propagator is too noisy. — This is basically because the static self-energy contains $1/a$ power divergence. ALPHA collaboration introduced a static action with link smearing which improves the signal to noise ratio.[2]

ii Non-perturbative matching with the continuum is needed. — If we include $O(1/m_b)$ correction in the HQET formulation, the continuum limit cannot be reached by perturbative matching factor because of power divergence.[3]

As a first step in this project, the static approximation (lowest order of the HQET) is a valuable and important approach to the complete HQET. In the static limit, the perturbative matching procedure is justified. In this report we mainly focus on the $O(a)$ improvement of operators, and then treat the matching factor between continuum HQET (CHQET) and lattice HQET (LHQET).

We use the Iwasaki gluonic action and the domain-wall (DW) fermion with light quark mass m_q for the light quark (q) sector. In calculation of the matching factor, it is assumed that the extension of the 5th dimension is infinity, which means the light quarks have exact chiral symmetry. For the heavy quark (h) sector, we use the static approximation with link smearing. The choices of the smearing are APE, HYP1 and HYP2.

Here we consider the static heavy-light quark bilinear and $\Delta B = 2$ four-quark operator. The on-shell $O(a)$ improved LHQET operators matched with CHQET have following form:

Quark bilinear operator

$$O_\Gamma = Z\left(1 + bGm_q a\right)\left[O_\Gamma^{(0)} + cGaO_\Gamma^{(1)}\right], \qquad (1)$$

with $O_\Gamma^{(0)} = \bar{h}\Gamma q$ and $O_\Gamma^{(1)} = \bar{h}\Gamma\vec{\gamma}\cdot\vec{D}q$ with $\Gamma = \{1, \gamma_\mu, \gamma_5, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$. Z is the overall matching factor; c and b are the $O(pa)$ and $O(m_q a)$ improvement coefficient, respectively; and they are all independent on Γ. G is defined by $\gamma_0\Gamma\gamma_0 = G\Gamma$.

Four-quark operator ($\Delta B = 2$)

$$O_L = Z_L\left[O_L^{(0)} + Z_L^{(1)}aO_{ND} + Z_L^{(m)}m_q aO_N\right], \quad (2)$$

with

$$O_L^{(0)} = 2[\bar{h}^{(+)}\gamma_\mu^L q][\bar{h}^{(-)}\gamma_\mu^L q], \qquad (3)$$

$$O_{ND} = 2[\bar{h}^{(+)}\gamma_\mu^R(\gamma_i\vec{D}_i)q][\bar{h}^{(-)}\gamma_\mu^L q] \qquad (4)$$
$$+4[\bar{h}^{(+)}P_R(\gamma_i\vec{D}_i)q][\bar{h}^{(-)}P_L q] + \{(+) \longleftrightarrow (-)\},$$

$$O_N = 2[\bar{h}^{(+)}\gamma_\mu^R q][\bar{h}^{(-)}\gamma_\mu^L q] \qquad (5)$$
$$+4[\bar{h}^{(+)}P_R q][\bar{h}^{(-)}P_L q] + \{(+) \longleftrightarrow (-)\},$$

where $h^{(+)}(h^{(-)})$ is the particle (anti-particle) of the static quark, $\gamma_\mu^L = \gamma_\mu P_L$ and $\gamma_\mu^R = \gamma_\mu P_R$. Z_L is an overall matching factor, and $Z_L^{(1)}$ and $Z_L^{(m)}$ are the $O(pa)$ and $O(m_q a)$ improvement coefficient, respectively.

The matching factor and the $O(a)$ improvement coefficients are calculated using one-loop perturbation theory. The calculation is performed by comparing the transition amplitude for the CHEQT and the LHQET. In order to extract the on-shell $O(a)$ improvement coefficients, the amplitude is expanded in the external quark momenta around zero momentum and the light quark mass m_q around zero mass. The UV divergences in the continuum calculation are regulated by dimensional regularization and we use the $\overline{\text{MS}}$ scheme for the renormalization. The IR divergences are regulated by introducing the gluon mass λ.

Now we roughly estimate these $O(\alpha_s a)$ effects for physical quantities using the actual simulation data from the 2+1 flavor dynamical DW QCD project by RBC and UKQCD Collaborations ($\beta = 2.13$, $L^3 \times T \times L_5 = 16^3 \times 32 \times 16$, $M_5 = 1.80$, $m_{ud}a = \{0.01, 0.02, 0.03\}$, $m_s a = 0.0359$) which appeared in Ref. 4). For this estimate the MF-improvement is taken into account. The coupling constant has the conservative range $\alpha_s \sim 0.15 - 0.35$. The conclusion is that the $O(\alpha_s a)$ effect of the B meson decay constant f_B is $3 - 8\%$(APE) and $5 - 12\%$(HYP2); the effect of $B^0 - \bar{B}^0$ mixing matrix element $\mathcal{M}_B$ is $9 - 24\%$(APE) and $15 - 36\%$(HYP2); and the effect of the SU(3) breaking ratio ξ is less than 2%. Then, the $O(a)$ improvement gives a non-negligible effect at one-loop perturbation. While perturbative matching has large ambiguities and its own limitations, we deduce that this conclusions is not largely changed even in non-perturbative matching.

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Thermal Noise in AdS/CFT

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The AdS/CFT Correspondence is a useful tool to study the physics of strong coupling. In the field of heavy ion phenomenology, interest in the AdS/CFT correspondence began when Policastro, Son and Starinets[1] and Kovtun, Son and Starinets[2] determined the shear viscosity (η) to entropy (s) ratio of the $\mathcal{N} = 4$ SYM plasma

$$\frac{\eta}{s} = \frac{1}{4\pi}. \tag{1}$$

This ratio is of order the ratio extracted from the RHIC results. The link between the correspondence and the experiments is tantalizing but circumstantial. Many more phenomenologically interesting observables may be computed within this framework and will clarify whether the predictions of $\mathcal{N} = 4$ are qualitatively correct.

Recently, former Stony Brook student Jorge Casalderrey and I determined the diffusion coefficient of a heavy quark using the AdS/CFT correspondence[5]

$$D = \frac{2}{\sqrt{\lambda}\pi T}. \tag{2}$$

This transport property may be relevant to the interpretation of the heavy flavor data at RHIC.

It is interesting that a diffusion coefficient can be predicted from the classical AdS/CFT correspondence. How can a stable linearized classical theory be the dual of a stochastic Brownian particle?

Indeed one of the most troubling aspects of the AdS/CFT correspondence is the apparent absence of the thermal noise. This seems at odds with the fluctuation-dissipation theorem and leads to some seemingly incorrect results from the correspondence. For instance, it predicts the absence of long-time hydrodynamic tails zero drag on mesons and the lack of Brownian motion of a quark string in AdS$_5$. In many cases, the effect of thermal noise is suppressed either by large N or large λ, and therefore these inconsistencies with field theory intuition were rationalized as an artifact of these restrictive limits. In Ref.[3] we overcame these difficulties by working through the simplest possible system which should exhibit drag and noise in AdS/CFT. This system is the Brownian motion of a heavy quark placed in the $\mathcal{N} = 4$ SYM plasma.

In particular we worked out a bulk picture of fluctuations experienced by a heavy quark string in AdS$_5$. A thermalized quark string in AdS$_5$ experiences drag and noise. The physical picture that emerges when observing the quark is the following: In the long time limit, the motion can be regarded as stochastic. Then at each time step $t_1, t_2, t_3 \ldots$, the quark string fluctuates to a new configuration which is perceived as a random force on the boundary. The average string is perceived as a drag and corresponds to the "trailing string" solution of Ref.[6,7].

Now work is in progress to compute the statistical fluctuations and diffusion of charmonium and other mesonic states in D-brane constructions. Although transport of these states is generally suppressed by $1/N_c$, the diffusion coefficient of a heavy meson was computed this year by appealing to the boundary fluctuation dissipation theorem[4]. Given the bulk picture of fluctuations developed in Ref.[3] a new understanding of this calculation is the following: The gravitational fields and dilatonic fields are continually fluctuating. Since these fluctuating gravitational and dilatonic fields shift the spectrum of the D7 brane excitations, gradients in these fields give rise to a net force on a mesonic normal modes of the D7 brane. This force jostles the heavy meson causing it to diffuse.

The work also suggest new direction for the study of fast quarks with AdS/CFT. For instance, it should be possible to compute the fluctuations of the average energy within a cone of a jet. Currently, the experimentalists are studying three particle correlations which probe this sort of physics. Many additional observables can be proposed and ultimately measured. There is much work to establish a good set fluctuation measures and to calculate these measures with kinetic theory and the AdS/CFT. Ultimately this analysis should establish the relevance or irrelevance of the AdS/CFT correspondence to the heavy ion reaction.

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Extended MQCD and SUSY/non-SUSY duality[†]

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[Geometric engineering, Calabi-Yau geometry, N=1 gauge theory]

Recently, Aganagic et al. proposed a SUSY/non-SUSY duality[1] in Type IIB string compactification. In contrast to previous works where anti-branes are introduced by hand, the breakthrough was to turn on a holomorphic varying background NS-flux H_0 through the non-compact Calabi-Yau (CY) three-fold. This soon suggests a way to realize various kinds of SUSY or non-SUSY vacua via adjusting parameters the NS-flux contains.

Let us briefly review their ideas. Because of the flux $H_0 = dB_0$, four-dimensional gauge theory, realized by wrapping D5-branes on vanishing two-cycles of a CY, acquires different gauge couplings at each P^1 locus: $\alpha = \frac{\theta}{2\pi} + \frac{4\pi i}{g_{YM}^2} = \int_{P^1} B_0(v)$, $B_0 = B_{RR} + \frac{i}{g_s} B_{NS}$, where v parameterizes a CY bearing, say, the A_1-type singularity as $X : uz + w^2 - W'(v)^2 = 0$. Note that $W(v) = \sum_{k=1}^{n+1} a_k v^k$, providing a non-trivial A_1 fibration over v, corresponds to the tree-level superpotential breaking $\mathcal{N} = 2$ down to $\mathcal{N} = 1$.

The proposed SUSY/non-SUSY duality is achieved by tuning coefficients of the v-dependent background B-field, which has the following expression $B_0(v) = \sum_{k=0}^{n-1} t_k v^k$. For generic t_k, SUSY is spontaneously broken at UV. This is accounted for by the fact that P^1's may develop relatively different orientations at critical points $W'(v) = \prod_{i=1}^{n}(v - v_i) = 0$ for $\int B_{NS} \sim$ Kähler moduli of P^1. On the other hand, some specific choice of t_k can still make four supercharges preserved, i.e. all orientations of P^1's are kept aligned. Trough geometric transition to dual CY manifolds, SUSY breaking effects can as well be captured qualitatively by studying strongly-coupled IR physics. Minimizing the effective superpotential there, one can further determine t_k from a_k[a].

Like the brane realization of meta-stable SUSY breaking vacua, our purpose in this paper is to translate things considered above into Type IIA/M-theory language. It is well-known that via a T-duality acting on X one instead obtains two NS5-branes in flat spacetime with D4-branes in between them. From the tree-level F-term $\int d^2\theta\, \mathcal{F}''_{UV}(\Phi)\mathcal{W}_\alpha \mathcal{W}^\alpha + W(\Phi)$, one can choose a vacuum $\Phi = diag(v_1, \cdots, v_2, \cdots, \cdots, v_n, \cdots)$ such that the gauge group $U(N)$ is broken to $\prod_{i=1}^{n} U(N_i)$. Then, it is seen that D4-branes, coming from IIB fractional D3-branes, remain at v_i's. The size and orientation of P^1's are translated, respec-

tively, to the length along the T-dual direction (bare gauge coupling) and sign of RR charge of i-th stack of D4-branes. Based on this Type IIA tree-level description[b], $B_{NS}(v) < 0$ which naively means negative gauge couplings can be understood as two crossing NS5-branes that result in anti-branes. How spontaneously SUSY breaking vacua occur can therefore be visualized clearly in the presence of both D4- and $\overline{D4}$-branes as a consequence of the *extended* prepotential.

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[a] This fact can be interpreted from M-theory perspective.

[b] As usual, we notice that tree-level field theory results match with classical brane pictures at the lowest order in ℓ_s under $g_s \to 0$, i.e. brane bending and string interaction are not taken into account.

Kerr/CFT correspondence and five-dimensional BMPV black holes[†]

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[AdS/CFT correspondence, 5D rotating Black holes]

Considerable progress in deriving black hole entropy statistically has been made by resorting to state counting approaches. Among them, while Cardy's formula in conformal field theory (CFT) plays an indispensable role, this can be better understood in the context of AdS/CFT correspondence via string compactification and wrapped branes[1]. For example, a 2D $\mathcal{N} = (0,4)$ CFT living on an M5-brane wrapping spatially $S^1 \times P_4$ ($P_4 \subset CY_3$) was shown to be dual to a 5D black hole formed by M-lifting a Type IIA D0-D4 system which has an attractor geometry near the horizon[2]. The entropy in terms of Cardy's formula $2\pi\sqrt{c_L L_0/6}$ agrees with Bekenstein-Hawking area law. Here c_L denotes the central charge and L_0 is the eigenvalue of the left-moving Virasoro zero mode.

On the other hand, an alternative pioneered much earlier by Brown and Henneaux[3] is to take into account the asymptotic symmetry preserved at the boundary. They dealt with a 3D BTZ black hole, which asymptotically approaches AdS_3 with $SL(2,R)_L \otimes SL(2,R)_R$ isometry. There, two copies of Virasoro algebra emerge as a result of infinitely many Fourier modes of the boundary diffeomorphism $\xi^\mu(x)\partial_\mu$. The central term arising from commutators of Virasoro generators was thereby used to reproduce the entropy $S_{BTZ} = 2\pi\sqrt{c_L L_0/6} + 2\pi\sqrt{c_R \tilde{L}_0/6}$. Note that no dynamical detail about this dual non-chiral CFT was given though.

In much the same spirit of Brown-Henneaux, chiral auxiliary 2D CFTs dual to 4D extremal Kerr black holes have recently been proposed by Strominger et al.[6]. On the near-horizon geometry a crucial boundary condition is imposed such that the asymptotic symmetry group (ASG) includes ultimately two kinds of generators, K^t and K_n^ϕ.

Quite remarkably, by further introducing Frolov-Thorne temperature T_{FT}[7], Cardy's formula $S = \frac{\pi^2}{3}c T_{FT}$ reproduces the macroscopic entropy perfectly. This aspect seems rather puzzling because it departs from our usual understanding instructed by BTZ black holes. There, neither their stringy derivation nor Brown-Henneaux method involves the underlying temperature T_{FT}.

In this article, we apply the above procedure to a well-known five-dimensional extremal supersymmetric charged spinning black hole constructed by Brecken-

ridge, Myers, Peet and Vafa (BMPV)[9]. Unlike Kerr-Newman black holes, this solution still exhibits unbroken supersymmetry even extremality is satisfied. As BTZ black holes mentioned above, the microscopic origin of BMPV entropy first roots in its D-brane realization. Nevertheless, the degeneracy counting that we will derive below will rely thoroughly on Virasoro algebra from ASG and Frolov-Thorne temperature. We remark that BMPV solutions have finite horizons and are asymptotically flat. Therefore, they are distinguished from another kind of 5D black holes formed by a M-theory lift of D0-D2-D6 systems.

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Toward a Proof of Montonen-Olive Duality via Multiple M2-branes[†]

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[4D super Yang-Mills theory, 3D super-conformal Chern-Simons theory, Montonen-Olive duality]

Among recent developments on effective actions of multiple M2-branes, one of the surprising outputs is the non-abelian duality. In 3 dimensions, it has been known for more than a decade that the action of a single M2-brane can be dualized classically to that of a D2-brane: an abelian duality between scalar field theory and 3d electromagnetism. Based on Bugger-Lambert-Gustavsson model[2)3)] of multiple M2-brane, Mukhi and Papageorgakis have obtained a quite intriguing non-abelian duality[4)], a relation between field theories on multiple M2-branes and D2-branes. In this paper, we generalize their result and find a novel mechanism to prove the renowned Montonen-Olive (MO) duality conjectured[1)] for 4d $\mathcal{N} = 4$ $U(N)$ super Yang-Mills (SYM) theory.

The method of Mukhi et al. is as follows. First, one of the eight transverse fields is given a vacuum expectation value (vev) v, which turns out to provide mass terms for a non-dynamical part of gauge fields in Chern-Simons (CS) terms. Integrating massive modes out, one gets rightly a YM kinetic term of D2-branes. As pioneered by Aharony, Bergman, Jafferis and Maldacena (ABJM)[5)], following the renormalization group, certain $\mathcal{N} = 3$ 3d CSYM theories flow to $\mathcal{N} = 6$ superconformal field theories (SCFTs) at IR fixed point, which precisely describe M2-branes probing $\mathbf{C}^4/\mathbf{Z}_k$ ($k > 2$) where k is the CS level. Equipped with these, the need for a vev then gets clarified geometrically, i.e. the M-theory circle is created in the above limit and D2-branes appear thereof. It is highly non-trivial that this mechanism requires CS terms which in turn give an orbifold moduli space.

Let us extend the step further to 4-dimensional theories. Let us summarize how $\mathcal{N} = 4$ SYM, 3d SCFT and MO duality are related to each other. As is well known, the axio-dilaton τ of Type IIB supergravity coincides with the gauge coupling of $\mathcal{N} = 4$ SYM, realized on N coincident D3-branes at low energy. MO duality is then regarded as S-duality of Type IIB string theory. In terms of M-theory, τ is interpreted as the complex structure of a two-torus formed by (x^9, x^{11}) such that the S-duality gets readily identified with the $SL(2, \mathbf{Z})$ modular transformation. Also, via duality chains, M2-branes transverse to the above two-torus with shrinking size and fixed τ guarantee that D3-branes they are dual to are non-compact.

To get a torus, it is insufficient to just dwell in the present ABJM model. We make use of a generalized version where the gauge group is $\prod_{i=1}^{2n} U(N)_i$. As shown in[6)], it is possible to prepare a IIB brane setup which flows to the theory we want at IR fixed point. Viewed from M-theory, this describes N M2-branes probing an abelian orbifold $\mathbf{C}^4/\Gamma$ where $\Gamma = \mathbf{Z}_n \times \mathbf{Z}_{kn}$.

We turn on vevs $(v, \tilde{v})$ of two scalars and make a torus using a crucial scaling limit which carries out the shrinking size with fixed τ. Our field theory result shows that a 4d SCFT (SYM theory) emerges from a 3d SCFT (generalized ABJM model) as desired. Methods for uplifting dimensions are basically Taylor's T-duality[7)] and deconstruction of extra dimensions[8)]. With the SYM obtained, we go further to analyze MO duality. It is found that there are infinitely many equivalent SYMs derived from the same generalized ABJM action. But eventually they differ merely up to $SL(2, \mathbf{Z})$ redefinition of τ. This completes our proof of MO duality.

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D-brane States and Annulus Amplitudes in OSp Invariant Closed String Field Theory†

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[String field theory, D-branes, BRST symmetry]

D-branes have been studied for many years and used to reveal nonperturbative aspects of string theory. As Sen argued,[1] D-branes can be realized as soliton solutions to the equation of motion in open string field theory. Now some of his conjectures have been proved analytically[2] in Witten's open string field theory.

In previous works,[3] we studied how D-branes can be realized in closed string field theory. A fairly clear answer to this question is given for noncritical strings. Fukuma and Yahikozawa[4] showed that D-branes can be realized as solitonic operators which commute with the Virasoro and the W constraints for noncritical string theories. Hanada et al.[5] showed how such solitonic operators can be realized in the string field theory for noncritical strings presented in Ref. 6). We showed[3] that a similar construction is possible in the case of critical strings, using the OSp invariant string field theory. We constructed states with an arbitrary number of coincident D-branes in this theory. Imposing the condition that the states should be BRST invariant, we can determine the form of the states. In particular, the tension of the D-branes is fixed to be the correct value. We can calculate disk amplitudes using these states, and the results indeed coincide with those of first quantized string theory. A key to the proof of the BRST invariance of the above-mentioned D-brane states is the idempotency relation satisfied by the boundary state.[7]

The purpose of this work is to extend our construction into the case where the parallel D-branes are located at different points from each other in space-time. Using such states with the D-branes, we would like to evaluate scattering amplitudes involving strings whose worldsheet have boundaries attached to D-branes contained in these states. In this report, we compute annulus amplitudes with closed string external lines, in the situation where the annulus is suspended between two parallel D-branes. We show that they coincide with the usual annulus amplitudes including the normalizations. This fact yields further evidence for our construction.

The BRST invariant state corresponding to one flat Dp-brane sitting at $X^i = Y^i$ $(i = p + 1, \ldots, 25)$ takes the form[3]

$$|D(Y)\rangle\!\rangle = \lambda \int d\zeta \, \bar{\mathcal{O}}_D(\zeta, Y)|0\rangle\!\rangle \,, \tag{1}$$

$$\bar{\mathcal{O}}_D(\zeta, Y) = \exp\left[A \int_{-\infty}^{0} \frac{d\alpha}{4\pi} e^{\zeta\alpha} \langle B^\epsilon | \bar{\psi}(\alpha)\rangle + B\zeta^2 \right] \,,$$

$$A = \frac{1}{2}\sqrt{\frac{\pi}{256}(8\pi^2)^{11-p}} \,, \quad B = \frac{2^{\frac{19+p}{2}}\epsilon^2(-\ln\epsilon)^{\frac{p+1}{2}}}{\pi^{\frac{p-24}{2}}g} \,,$$

where $|B^\epsilon(Y)\rangle = e^{-\epsilon H}|B(Y)\rangle$ is a regularization (with an infinitesimal regularization parameter ϵ) of the boundary state $|B(Y)\rangle$ for the Dp-brane located at $X^i = Y^i$, H is the tree-level hamiltonian, g is the string coupling constant, and $|\bar{\psi}\rangle$ is the creation operator of a string. We find that the state corresponding to N such Dp-branes located at $X^i = Y^i_{(I)}$ $(I = 1, \ldots, N)$ is given simply as

$$|D_N; Y_{(I)}\rangle\!\rangle = \lambda_N \prod_{I=1}^{N} \left(\int d\zeta_I \, \bar{\mathcal{O}}_D(\zeta_I, Y_{(I)}) \right) |0\rangle\!\rangle \,, \tag{2}$$

if $(Y_{(I)} - Y_{(J)})^2 \neq 0$ for $I \neq J$. In contrast to the case of coincident D-branes,[3] we just have to consider the product of $\int d\zeta \, \bar{\mathcal{O}}_D$'s. The idempotency relation[7] is again a key to the proof of the BRST invariance of this state.

Following the prescription given in Ref. 8) to evaluate the S-matrix elements in the OSp invariant string field theory, we compute the annulus amplitudes mentioned above, by using the D-brane state (2). We find that the results in the first quantized string theory are reproduced with the correct normalization. The annulus amplitude is expressed as an integral over the moduli space of string worldsheet for the process. We notice that in this integral, the moduli space is covered completely and only once with the correct measure. This verifies the validity of our construction.

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Gauge invariant overlaps for classical solutions in open string field theory[†]

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[Nonperturbative techniques, string field theory, D branes, conformal field theory]

After the advent of Schnabl's analytic solution[1] for tachyon condensation in Witten's cubic bosonic open string field theory, there have been a number of new developments in this field. A prominent feature is the potential height at the solution, which is equal to the tension of D25-brane as is consistent with Sen's conjecture. Here, we calculate other gauge invariant observables,[2–4] which will be called gauge invariant overlaps, for Schnabl's solution with an analytic method and with level truncation approximation. We also compute these for the numerical solution[5,6] initially obtained by Sen and Zwiebach in the level truncation approximation to compare with those for Schnabl's solution. The results are consistent with the expectation that these solutions may be gauge equivalent.

Gauge invariant overlap $\mathcal{O}_V(\Psi)$ for an open string field Ψ is defined by

$$\mathcal{O}_V(\Psi) \equiv \langle V(i) f_{\mathcal{I}}[\Psi] \rangle, \quad f_{\mathcal{I}}(z) = \frac{2z}{1-z^2}, \qquad (1)$$

where the CFT correlator is defined on the upper half plane and the operator $V(i)$ inserted at the midpoint of the string field corresponds to an on-shell closed string state. $\mathcal{O}_V(\Psi)$ is left invariant under the gauge transformation of the open string field theory:

$$\delta\Psi = Q_B\Lambda + \Psi * \Lambda - \Lambda * \Psi \qquad (2)$$

with a gauge parameter string field Λ. Note that (1) vanishes for pure gauge solutions.

Schnabl's analytic solution[1] can be expressed as

$$\Psi_\lambda = \frac{\lambda\partial_r}{\lambda e^{\partial_r} - 1}\psi_r|_{r=0} \qquad (3)$$

with one parameter λ, where ψ_r is a particular string field based on the wedge state $|r+2\rangle$. We have computed $\mathcal{O}_V(\psi_r)$ analytically and found that it is independent of r. Therefore, we conclude[a]

$$\mathcal{O}_V(\Psi_\lambda) = \begin{cases} \frac{C_V}{2\pi i} & (\lambda = 1) \\ 0 & (\lambda \neq 1) \end{cases}. \qquad (4)$$

(C_V is determined by the normalization of $V(i)$ in (1).) That is, the gauge invariant overlap for Ψ_λ becomes nontrivial only in the case $\lambda = 1$. Our result is consistent with the previous evaluation of the potential height and suggests that $\Psi_{\lambda=1}$ represents a nonperturbative vacuum and $\Psi_{\lambda\neq1}$ gives pure gauge solutions.

We have also numerically computed $\mathcal{O}_\eta(\Psi_\lambda)$ for $|\lambda| \leq 1$ with the conventional L_0-level truncation approximation. Here $V(i)$ in (1) corresponds to the dilaton state with zero momentum, which gives $C_V = i$ in (4). For the interval $-1 \leq \lambda < 1$, $\mathcal{O}_\eta(\Psi_{\lambda,L})$ approaches zero as the level L is increased. For $\lambda = 1$, $\mathcal{O}_\eta(\Psi_{\lambda=1,L})$ approaches $1/(2\pi) \simeq 0.159155$ as in Table 1. This is consistent with our analytic result in (4).

L	$\mathcal{O}_\eta(\Psi_{\lambda=1,L})$
0	0.138366
2	0.149284
4	0.156857
6	0.157395
8	0.158795
10	0.158765
12	0.159220
14	0.159159

Table 1.

We also computed the gauge invariant overlap for the numerical solution Ψ_N in the Siegel gauge, which is obtained by $(L, 2L)$ and $(L, 3L)$ truncation. The result is given in Table 2. The best approximation ($(10, 30)$ truncation) gives 97% of $1/(2\pi)$. Therefore, $\mathcal{O}_\eta(\Psi_N) \simeq \mathcal{O}_\eta(\Psi_{\lambda=1})$. In addition to the matching of potential height, this gives further evidence for the gauge equivalence of Ψ_N with $\Psi_{\lambda=1}$, which implies that these two solutions give the same nonperturbative vacuum in the bosonic open string field theory.

L	$\mathcal{O}_\eta(\Psi_{N,(L,2L)})$	$\mathcal{O}_\eta(\Psi_{N,(L,3L)})$
0	0.114044	0.114044
2	0.139790	0.141626
4	0.147931	0.148325
6	0.151225	0.151369
8	0.152887	0.152976
10	0.154029	0.154080

Table 2.

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[a] This result was also given by Ellwood.[7]

Schnabl's solution and boundary states in open string field theory [†]

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[Nonperturbative techniques, string field theory, D branes, conformal field theory]

We discuss the fact that Schnabl's solution[1] is an off-shell extension of the boundary state describing a D-brane in the closed string sector. This gives the physical meaning of the gauge invariant overlaps for the solution in our previous paper[2] and supports Ellwood's recent proposal[3] in the operator formalism.

The Schnabl solution for tachyon condensation $\Psi_{\lambda=1}$ can be rewritten as

$$\Psi_{\lambda=1} = \psi_0 + \sum_{n=0}^{\infty}(\psi_{n+1} - \psi_n - \partial_r\psi_r|_{r=n})$$
$$\equiv \psi_0 + \chi. \tag{1}$$

Since it has been shown[2,3] that $\mathcal{O}_V(\psi_r)$ does not depend on r, it is evident that

$$\mathcal{O}_V(\Psi_{\lambda=1}) = \mathcal{O}_V(\psi_0). \tag{2}$$

This suggests that only the first term ψ_0 contributes to the gauge invariant overlaps $\mathcal{O}_V(\Psi_{\lambda=1})$.

Recently, Ellwood has made the interesting proposal that the gauge invariant overlaps are related to the closed string tadpoles as follows[3]

$$\mathcal{O}_V(\Psi) = \mathcal{A}_\Psi(V) - \mathcal{A}_0(V), \tag{3}$$

where $\mathcal{A}_\Psi(V)$ is the disk amplitude for a closed string vertex operator V with the boundary condition of the CFT given by the open string field solution Ψ, and $\mathcal{A}_0(V)$ is the usual disk amplitude in the perturbative vacuum. In fact, he has shown this to be the case for some analytic solutions. Since there are no D-branes after tachyon condensation, no closed tadpoles are available, and thus $\mathcal{A}_\Psi(V) = 0$. Therefore, the gauge invariant overlap for the tachyon vacuum solution gives the usual disk amplitude of the opposite sign with one closed string emitted. This suggests that, as expected, the analytic solution given by Schnabl is closely related to the boundary state describing a D-brane in the closed string perturbation theory.

Here, we will explicitly demonstrate this in the operator formalism of string field theory by using the Shapiro-Thorn vertex $\langle\hat{\gamma}(1_c,2)|$, which maps an open string state to the corresponding closed string state. By using the open-closed string vertex $\langle\hat{\gamma}(1_c,2)|$, as discussed in detail in our previous paper[2] we can rewrite a gauge invariant overlap as

$$\mathcal{O}_V(\psi) = \langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\psi\rangle_2, \tag{4}$$

where $|\phi_c\rangle_{1_c}$ is an on-shell state corresponding to the

vertex operator V of the closed string 1_c, and $|\psi\rangle_2$ is a state of the open string 2. For the analytic solution $\Psi_{\lambda=1}$ (1), we have

$$\mathcal{O}_V(\Psi_{\lambda=1}) = \langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\Psi_{\lambda=1}\rangle_2$$
$$= \langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\psi_0\rangle_2 + \langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\chi\rangle_2 \tag{5}$$

and, as mentioned above (2), the second term on the right hand side is zero for the on-shell closed string state $|\phi_c\rangle_{1_c}$. For the first term on the right hand side, $\langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\psi_0\rangle_2$, we can see that the open string tachyon state $|\psi_0\rangle = (2/\pi)c_1|0\rangle$ is transformed via the vertex $\langle\hat{\gamma}(1_c,2)|$ into the boundary state $\langle B|$. In fact, we can obtain the relation

$$\langle\hat{\gamma}(1_c,2)|\psi_0\rangle_2\mathcal{P}_{1_c} = \frac{1}{2\pi}\langle B|c_0^- \tag{6}$$

with the level matching projection $\mathcal{P}_{1_c}$ for the closed string 1_c, where the boundary state is the usual one:

$$\langle B| = \langle 0|c_{-1}\bar{c}_{-1}c_0^+ e^{-\sum_{n=1}^{\infty}[\frac{1}{n}\alpha_n\cdot\bar{\alpha}_n + c_n\bar{b}_n + \bar{c}_n b_n]} \tag{7}$$

in the closed string perturbation theory. We thus find that

$$\mathcal{O}_V(\Psi_{\lambda=1}) = \frac{1}{2\pi}\langle B|c_0^-|\phi_c\rangle, \tag{8}$$

which is in precise agreement with Ellwood's result.

Since the second term on the right hand side of (5) does not necessarily vanish for off-shell closed string states, we may conclude that the transform of the analytic solution $\Psi_{\lambda=1}$ via the Shapiro-Thorn vertex is an off-shell extension of the boundary state $|B\rangle$. Although it seems more complicated to calculate $\langle\hat{\gamma}(1_c,2)|\phi_c\rangle_{1_c}|\chi\rangle_2$, it would be interesting to find the relation of the off-shell boundary state with the equation of motion in closed string field theory[5–8] or open-closed string field theory[9]. We believe that our observation above may serve as an encouraging step in this investigation.

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Comments on gauge invariant overlaps for marginal solutions in open string field theory †

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[Nonperturbative techniques, string field theory, D branes, conformal field theory]

We calculate the gauge invariant overlap[a] for the marginal solution with nonsingular current given by Schnabl[2] and Kiermaier-Okawa-Rastelli-Zwiebach[3] (S/KORZ). The obtained formula is the same as that for the Fuchs-Kroyter-Potting/Kiermaier-Okawa (FKP/KO) marginal solution,[4,5] which has already been computed by Ellwood.[7] Our result is consistent with the expectation that these two types of solutions may be gauge equivalent. We also comment on a gauge invariant overlap for rolling tachyon solutions in cubic bosonic open string field theory.

The gauge invariant overlap $\mathcal{O}_V(\Psi)$ is written as

$$\mathcal{O}_V(\Psi) = \langle \mathcal{I}|V(i)|\Psi\rangle, \tag{1}$$

where $\langle \mathcal{I}|$ is the identity state and $V(i)$ corresponds to an on-shell closed string state. Next, we can prove the following relations:

$$\langle \mathcal{I}|V(i)K_n = 0, \qquad K_n \equiv L_n - (-1)^n L_{-n}, \tag{2}$$

$$\langle \mathcal{I}|V(i)(b_n - (-1)^n b_{-n}) = 0, \tag{3}$$

$$\langle \mathcal{I}|V(i)(c_n + (-1)^n c_{-n}) = 0. \tag{4}$$

Noting the above we can rewrite the S/KORZ marginal solution $\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}}$ as

$$\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}} = -\frac{1}{\pi} 2^{-\mathcal{L}_0} \left(e^{-\lambda_{\mathrm{m}} \int_0^{2\pi} d\theta J_w(e^{i\theta})} - 1 \right) c_1|0\rangle$$

$$+ O(K_1, \mathcal{L}_0 - \mathcal{L}_0^{\dagger}, \mathcal{B}_0 - \mathcal{B}_0^{\dagger}, c_n + (-1)^n c_{-n}). \tag{5}$$

Here, J_w is a matter primary operator with dimension one on the unit disk $|w| \leq 1$, which has nonsingular OPE, and λ_{m} is a parameter which corresponds to a marginal deformation of the boundary CFT. The second term $O(K_1, \mathcal{L}_0 - \mathcal{L}_0^{\dagger}, \mathcal{B}_0 - \mathcal{B}_0^{\dagger}, c_n + (-1)^n c_{-n})$ denotes some linear combination of terms comprising K_1, $\mathcal{L}_0 - \mathcal{L}_0^{\dagger}$, $\mathcal{B}_0 - \mathcal{B}_0^{\dagger}$ and $c_n + (-1)^n c_{-n}$, where at least one of them is multiplied on the conformal vacuum $|0\rangle$. $\mathcal{B}_0$ is the b-ghost zero mode on the sliver frame and $\mathcal{L}_0 = \{Q_{\mathrm{B}}, \mathcal{B}_0\}$. Using this decomposition (5)[b] and relations (2), (3) and (4), we can easily evaluate the gauge invariant overlap (1):

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[a] See, our previous paper[1] for technical details.

[b] Similar decompositions are possible for the FKP/KO marginal solution $\Psi_{\lambda_{\mathrm{m}},L}^{\mathrm{FKP/KO}}$ and Schnabl's solution for tachyon condensation[6] $\Psi_{\lambda}^{\mathrm{S}}$. They give another approach to computing the gauge invariant overlap (1) for the solutions evaluated in earlier papers.[1,7,8]

$$\mathcal{O}_V(\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}})$$

$$= -\frac{1}{2\pi i} \left\langle c^w \bar{c}^w V_{w\bar{w},\mathrm{m}}(0,0) \right. \tag{6}$$

$$\left. \times c^w(1) \left(e^{-\lambda_{\mathrm{m}} \int_0^{2\pi} d\theta J_w(e^{i\theta})} - 1 \right) \right\rangle_{\mathrm{disk}}.$$

The result is the same as the formula[7] for the FKP/KO marginal solution $\Psi_{\lambda_{\mathrm{m}},L}^{\mathrm{FKP/KO}}$,

$$\mathcal{O}_V(\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}}) = \mathcal{O}_V(\Psi_{\lambda_{\mathrm{m}},L}^{\mathrm{FKP/KO}}), \tag{7}$$

for the same $\lambda_{\mathrm{m}}J$. This is consistent with the expectation that $\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}}$ and $\Psi_{\lambda_{\mathrm{m}},L}^{\mathrm{FKP/KO}}$ are gauge equivalent.

Let us consider the gauge invariant overlap $\mathcal{O}_{V_\zeta}(\Psi)$ with $V_{\mathrm{m}} = \zeta_{\mu\nu} \partial X^\mu \bar{\partial} X^\nu$ $(\zeta_{\mu\nu} V^\nu = V^\mu \zeta_{\mu\nu} = 0)$ for Hellerman-Schnabl's solution[9] $\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}}$, which is given by $\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{S/KORZ}}$ with the light-like rolling tachyon operator $J = e^{\beta X^+}$, $(\beta \equiv 1/(\alpha'V^+))$, on the linear dilaton background $\Phi(x) = V_\mu x^\mu$, $(V^+ > 0, 26 = D + 6\alpha'V_\mu V^\mu, \mu = 0, 1, \cdots, D-1)$. Applying our formula (6) for $\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}}$ and using the formula of the CFT correlator,[9,10] we can evaluate $\mathcal{O}_{V_\zeta}(\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}})$ explicitly. On the other hand, for the tachyon vacuum solution $\Psi_{\lambda=1}^{\mathrm{S}}$, we have

$$\mathcal{O}_{V_\zeta}(\Psi_{\lambda=1}^{\mathrm{S}}) = -\frac{\alpha'}{4\pi i} \zeta_{\mu\nu} \eta^{\mu\nu} \int d^D x \, e^{-V\cdot x} \tag{8}$$

on this background. Then, we obtain the relation

$$\lim_{\lambda_{\mathrm{m}} \to +\infty} \mathcal{O}_{V_\zeta}(\Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}}) = \mathcal{O}_{V_\zeta}(\Psi_{\lambda=1}^{\mathrm{S}}). \tag{9}$$

This is consistent with the late time limit of the light-like rolling tachyon solution:[9]

$$\lim_{x^+ \to +\infty} \Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}} = \lim_{\lambda_{\mathrm{m}} \to +\infty} \Psi_{\lambda_{\mathrm{m}}}^{\mathrm{HS}} = \Psi_{\lambda=1}^{\mathrm{S}}. \tag{10}$$

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Electroweak symmetry breaking in $SO(5) \times U(1)$ gauge-Higgs unification with top and bottom quarks[†]

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[Extra dimension, gauge symmetry breaking]

The origin of electroweak symmetry breaking is still a mystery of elementary particle physics. In the standard model, it is broken by the vacuum expectation value of the Higgs field. However the Higgs boson has not been discovered yet, and searching to it is one of the main purposes of the Large Hadron Collider (LHC) experiment at CERN. Another aim of LHC is to discover evidence of new physics beyond the standard model. It is well known that the standard model has some theoretical problems, such as the gauge hierarchy problem. TeV-scale supersymmetry is one promising candidate for new physics that solves the gauge hierarchy problem. The supersymmetric models generically predict a relatively light Higgs boson. In the minimal supersymmetric standard model, for example, the Higgs mass is bounded below around 130 GeV, which is close to the experimental lower bound of 114 GeV. Under these circumstances, it is important to investigate candidates for new physics other than supersymmetry.

One important class of such candidates is extra dimensions. They are based on the idea that there are extra spatial dimensions other than the four-dimensional world we observe. Although these extra dimensions were originally introduced to explain the weakness of gravity compared to the other forces, they can also play an important role in solving other problems of the standard model. For instance, they can naturally realize the large hierarchy among the fermion masses, and can break gauge symmetries or supersymmetry by the boundary conditions along the extra dimensions. They also serve as a candidate for dark matter. For these reasons, models with extra dimensions have been studied extensively during the past decade.

Gauge-Higgs unification is an attractive idea for the origin of electroweak symmetry breaking in the context of extra dimensions. The basic idea is to identify the extra-dimensional components of the gauge field as the four-dimensional Higgs fields that break electroweak symmetry. This class of models has a theoretical advantage for the gauge hierarchy problem. The Higgs mass is protected against radiative correction by the higher dimensional gauge symmetry, and thus is insensitive to the ultra-violet cut-off scale of the models. Furthermore, these models provide interesting predictions for some masses and coupling constants in the four-dimensional effective theory because various quantities are related to each other due to the higher

dimensional gauge symmetry.

In spite of these virtues, the gauge-Higgs unification scenario on a flat geometry has some phenomenological problems. It predicts a Higgs particle which is too light, typically one order of magnitude lighter than the W boson, and the WWZ coupling may deviate significantly from that in the standard model. One way out of these problems is to consider this scenario in the Randall-Sundrum spacetime,[1] which is a solution of the five-dimensional Einstein equation[3] and is regarded as a slice of the five-dimensional anti-de Sitter space. Due to the warping geometry along the fifth dimension, it can explain the exponentially large hierarchy between the Planck and electroweak scales. Furthermore, the hierarchical pattern of the fermion masses can easily be realized in this spacetime by varying five-dimensional masses for fermions in an order one range compared to the five-dimensional Planck scale, which is the fundamental scale of the model. In our previous work,[1,2] we have studied various coupling constants in the gauge-Higgs sector and pointed out that they can be deviated from the counterparts in the standard model.

In the present work, we construct an explicit model based on an $SO(5) \times U(1)$ gauge theory in the Randall-Sundrum spacetime, focusing on the matter sector. The presence of fermions is vital to have electroweak symmetry breaking. The fermion content triggers electroweak symmetry breaking by quantum effects. Our model realizes observed matter content without any exotic light particles, and thus is a realistic model. One important prediction of this model is that the WWH- and the ZZH-couplings (H stands for the Higgs boson) vanish at the vacuum, which significantly affects Higgs production in collider experiments. This work leads to better understanding of the structure of gauge-Higgs unification models consistent with current experimental results.

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Vacuum energy of two-dimensional $\mathcal{N} = (2, 2)$ super Yang-Mills theory

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[supersymmetry, spontaneous breaking, lattice simulation]

Numerical simulation on the basis of lattice formulation provides a very powerful tool for non-perturbative study of field theory. On the other hand, lattice formulation of supersymmetric systems is essentially difficult and thus its numerical simulation was regarded difficult as well. In a recent work[1], however, we successfully realized numerical simulation of a two-dimensional supersymmetric gauge theory, $\mathcal{N} = (2, 2)$ super Yang-Mills theory. This report is based on one of its applications[2]. Among non-perturbative phenomena in supersymmetric systems, one of the most important things is the spontaneous supersymmetry (SUSY) breaking. SUSY is not realized in the current universe and must be spontaneously broken if it is a relevant symmetry in nature. However, it is known that spontaneous SUSY breakings occur only non-perturbatively unless broken in a tree level. Therefore, non-perturbative analysis by simulation can be a powerful tool for spontaneous SUSY breaking.

In this report, we measure the vacuum energy density $\mathcal{E}_0$, which is an order parameter for SUSY breaking. We use the expectation value of the Hamiltonian density $\mathcal{H}$ to measure $\mathcal{E}_0$[3,4]. There are two important points in this procedure. The first one is that we must correctly choose the origin of $\mathcal{H}$. As a result of SUSY algebra, $\mathcal{E}_0$ is zero if and only if SUSY is unbroken so we use the algebra to define $\mathcal{H}$ as well. The second point is that we use the thermal boundary condition and take a zero temperature limit afterwards. The temperature can be regarded as an external field conjugate to $\mathcal{H}$.

The simulation was performed on RIKEN Super Combined Cluster (RSCC). We use Rational Hybrid Monte Carlo (RHMC) algorithm to generate the configurations[5]. The complex phase of the Pfaffian of the lattice Dirac operator, which is neglected in the RHMC, is included as a reweighting factor in the measurement.

As shown in the previous work[1], we need to add a scalar mass term to the original lattice action in order to suppress fluctuations along the flat direction of the potential. We thus define the system by an extrapolation of $\mu^2 \to 0$ after taking the continuum limit, where μ is the scalar mass. In the extrapolation of $\mu^2 \to 0$ we use a linear function of μ^2, which fits very well to the data (Fig. 1). Although we use a lattice action with the scalar mass term to generate the configurations, we do not include the mass term to $\mathcal{H}$. In taking the continuum limit, we use 3–6 different lattice spacings. Since the gauge coupling g is dimensionful, we define
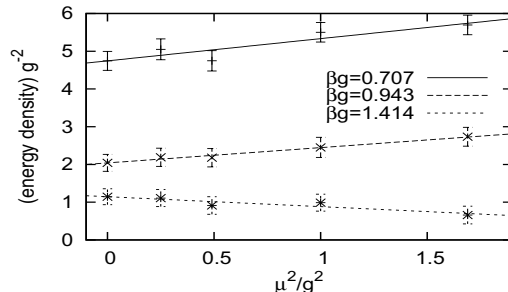
Fig. 1. Example of massless extrapolation.
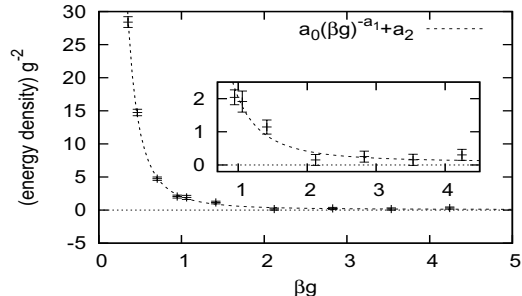
Fig. 2. Energy density as a function of the inverse temperature β.

the continuum limit as the bare dimensionless coupling ag goes to 0, where a is the lattice spacing. The lattice is isotropic and the temperature is controlled through changing temporal lattice size.

In Fig. 2, we plot the temperature dependence of the energy density, after extrapolating the scalar mass to zero. By fitting by a power function of β, we obtain $\mathcal{E}_0 = 0.09^{+10}_{-8} g^2$ as a value at $\beta \to \infty$, where errors denote statistical ones only. The obtained value is small compared with the typical scale of the system, and consistent with zero within the error. Although we cannot exclude a possibility of small non-zero vacuum energy, it seems to be consistent with no spontaneous SUSY breaking in this system. The full details including an analysis of the systematic errors will be presented in a forthcoming paper[2].

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Restoration of supersymmetry on the lattice: Two-dimensional $\mathcal{N} = (2, 2)$ supersymmetric Yang-Mills theory[†]

I. Kanamori and H. Suzuki

[supersymmetry, lattice gauge theory, Monte Carlo simulation]

It is widely believed that supersymmetry (SUSY) is an essential ingredient in particle physics beyond the Standard Model. Nonperturbative study of SUSY gauge theories from first principles is thus of great interest but it has always been elusive because the lattice formulation—only nonperturbative framework of gauge theories available to date—is irreconcilable with SUSY. Lattice structure explicitly breaks SUSY and one must generally fine-tune coefficients of relevant and marginal operators so that SUSY is recovered in the continuum limit. Such an intricate program is difficult to carry out practically within limited computational resources.

Given this situation, recently, for two- and three-dimensional extended SUSY gauge theories, lattice formulations that require no or a little fine tuning have been proposed. See Ref. 1) for a review. In these formulations, at least one fermionic symmetry that is a part of the full SUSY is manifested. This exact symmetry, combined with other lattice symmetries, (almost) prohibits relevant and marginal operators which break SUSY and other continuum symmetries. SUSY is then expected to automatically restored without or with a little fine tuning.

In the present study, we succeeded in numerically observing the restoration of SUSY in lattice formulation of the two-dimensional $\mathcal{N} = (2, 2)$ $SU(2)$ SUSY Yang-Mills theory (SYM), proposed by Sugino.[2] To our knowledge, this is the first demonstration of the SUSY restoration in lattice gauge theory.

As elucidated in the original paper, for some technical reasons, we need to introduce mass for the scalar fields that explicitly breaks SUSY. We also needed to adopt the thermal boundary condition that also explicitly breaks SUSY. With the present lattice setting, therefore, there are four possible sources for the SUSY breaking. That is, i) the scalar mass, ii) the thermal boundary condition, iii) the spontaneous SUSY breaking and iv) the lattice regularization itself. Among these, first three possesses physical meaning but the last effect is unphysical and should be eliminated. In this paper, we will discuss if the last unphysical effect disappear in the continuum limit or not upon the restoration of SUSY.

Generic correlation functions are affected by the four breaking effects in a mixed manner. Can we then isolate or separate the last effect? For this, we should observe the SUSY Ward-Takahashi identities in the
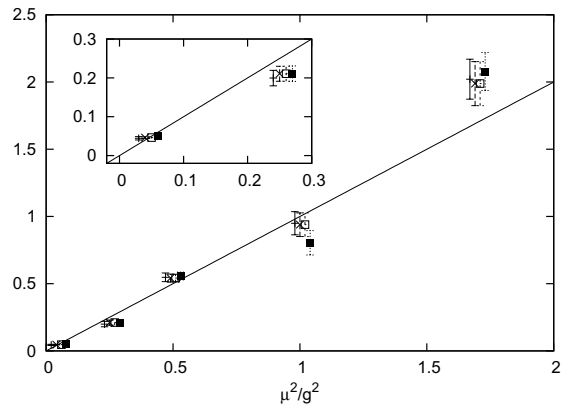
Fig. 1. The left-hand side of Eq. (1) as a function of the scalar mass squared μ^2/g^2. Symbols: $+$ for $i = 1$, $\times$ for $i = 2$, $\square$ for $i = 3$ and $\blacksquare$ for $i = 4$.

form of the partial conservation of the supercurrent ("PCSC" relation):

$$\frac{\partial_\mu \langle (s_\mu)_i(x)(f_0)_i(0) \rangle}{\langle (f)_i(x)(f_0)_i(0) \rangle} = \frac{\mu^2}{g^2}, \quad \text{for } x \neq 0. \qquad (1)$$

In this expression, s_μ is the supercurrent and f is a certain fermionic operator associated with the SUSY breaking scalar mass term. f_0 is an arbitrary gauge invariant fermionic operator and we used a lowest dimensional one. μ^2/g^2 is the scalar mass squared. The spinor index i runs over 1, 2, 3 and 4. This relation explicitly incorporates the effect on the scalar mass, and holds independently of the boundary condition and the spontaneous SUSY breaking. This relation, however, does not hold if the regularization breaks SUSY and thus isolates the unphysical effect.

The plot in Fig. 1, that was obtained by the extrapolation of Monte Carlo data to continuum, beautifully shows that relation (1) certainly holds in the continuum limit. This result strongly indicates that the full SUSY is restored in the continuum limit and the target continuum theory (i.e., the two-dimensional $\mathcal{N} = (2, 2)$ $SU(2)$ SYM with a soft SUSY breaking mass term) is realized as the continuum limit of the present lattice model.

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Some physics of the two-dimensional $\mathcal{N} = (2, 2)$ supersymmetric Yang-Mills theory:
A lattice Monte Carlo study[†]

I. Kanamori and H. Suzuki

[supersymmetry, lattice gauge theory, Monte Carlo simulation]

As reported elsewhere,[1] we have obtained affirmative numerical evidence that the two-dimensional $\mathcal{N} = (2, 2)$ $SU(2)$ supersymmetric Yang-Mills theory with a scalar mass term is realized as the continuum limit of a lattice model of Ref. 2). This result suggests the completely new possibility that the physical properties of a supersymmetric gauge theory (with a soft supersymmetry (SUSY) breaking mass) can numerically be studied. The aim of the present study is to illustrate this possibility.

As explored in Ref. 4), the correlation function between the $U(1)_V$ current and the $U(1)_A$ current in the present target theory in $\mathbb{R}^2$ is expected to exhibit power-like behavior. This implies that there exists a massless bosonic state and that there is no mass gap. As Fig. 1 shows, our Monte Carlo results reproduce this power-like behavior fairly well for $x_0 g \lesssim 1$. (The blow-up at $x_0 g \gtrsim 1$ is a reflection of the fact that our lattice is an approximation of a finite torus and not of $\mathbb{R}^2$.)

When the SUSY breaking scalar mass is small, we should have an approximately massless fermionic state corresponding to the above massless bosonic state, assuming that the spontaneous SUSY breaking does not occur. A SUSY Ward-Takahashi identity shows in

Fig. 2. Static potential energy $V(R)/g$ between probe charges in the fundamental representation of $SU(2)$. For parameters in each configuration set, see Ref. 3.

which correlation function such a fermionic state appears in as an intermediate state. Our Monte Carlo results confirmed this reasoning on the basis of (approximate) SUSY fairly well.

Armoni, Frishman and Sonnenschein[4] theoretically conjectured that a probe charge in the fundamental representation is screened in two-dimensional gauge theories containing a massless adjoint fermion. Our present target theory fulfills this criterion and thus it is of interest to observe the static potential between probe charges in the fundamental representation. Fig. 2 shows our result, obtained by a linear fit $\ln\{W(R, T)\} = V(R)T + c(R)$ of the expectation value of the Wilson loop $W(T, R)$ of size $T \times R$. Our result indicates that at least for $Rg \lesssim 1$ the static potential increases almost linearly. This confining behavior appears distinct from the above conjecture, according to which the static potential asymptotically approaches a constant. We have to systematically explore, however, the static potential for $Rg \gtrsim 1$ to determine the real asymptotic behavior.

Fig. 1. Correlation function between $U(1)_V$ current and $U(1)_A$ current along the line $x_1 = 0$ as a function of the coordinate x_0. For parameters in each configuration set, see Ref. 3). Broken line is the theoretical prediction for $\mathbb{R}^2$.[3]

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6. Development of Accelerator Facility

Acceleration Tests of ^{238}U and ^{48}Ca in RIBF

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Beam acceleration tests performed in the period from April 2008 to December 2008 are summarized in Table 1. The major purpose of the tests in the stand-alone mode of the RIKEN heavy-ion linac (RILAC)[1] is to investigate the lifetime of carbon foil strippers placed below RILAC. The tests indicate that the carbon foil lifetime is long enough for ^{48}Ca with the maximum beam intensity extracted from the 18-GHz ECR ion source[2], which corresponds to 500 pnA after extraction from the Superconducting Ring Cyclotron (SRC)[3]. On the other hand, the lifetime is less than 6 hours for Kr and heavier ions with the maximum intensity of the ion source. Details of the carbon foil tests are summarized by Hasebe et al.[4] in this report. The ^{48}Ca test started on May 27th aiming to evaluate the beam intensity of the ^{48}Ca beam. We successfully extracted 270 pnA of ^{48}Ca beam from the Intermediate-stage Ring Cyclotron (IRC)[5] under the use of a beam attenuator which reduces the beam intensity by a factor of 1.8. According to the result, a beam service time of ^{48}C beam was scheduled in December 2008.

Table 1 Summary of beam acceleration tests. The periods shown with the asterisk include beam service times, 18 days for ^{238}U and 11 days for ^{48}C, respectively.

Period	Particle	Accelerator used
4/08 – 5/02	^{238}U	RILAC to IRC
5/17 – 5/23	^{86}Kr	RILAC only
5/27 – 6/09	^{48}Ca	RILAC to IRC
6/26 – 7/10	^{238}U	RILAC to IRC
7/18 – 7/28	^{136}Xe	RILAC only
10/25 – 11/26*	^{238}U	RILAC to SRC
11/27 – 12/22*	^{48}Ca	RILAC to SRC

The uranium acceleration tests up to the IRC were performed to improve the transmission efficiency. The transmission efficiency of the whole accelerator complex of RIBF was limited to 2%, where charge stripping efficiencies are excluded[6]. We investigated reasons for the poor transmission efficiency and made various improvements in this year. The essential points are as follows. First, we upgraded the vacuum system of RILAC and its low-energy beam transport system to avoid beam losses caused by electron capture reaction with residual gases[7]. Secondly, the main differential probes of the fixed-frequency Ring Cyclotron (fRC)[8] and the SRC were modified[9]. The main differential probes measure turn patterns of the beams accelerated by our cyclotrons. Utilizing the fact that the turn pattern is very sensitive to the beam quality, we select appropriate voltages and phases of RF fields generated by the main and flattop cavities

installed in the cyclotrons. However, the secondary electrons emitted by uranium-ion bombardments and leakage RF fields from flattop cavities made it difficult to measure turn patterns precisely. These problems were solved just before the ^{48}Ca test started on November 27th. One of the other remaining problems is that the energy spread of the uranium beams injected into the fRC exceeds what is acceptable. It is a result of the poor uniformities of the stripper foils used before the fRC acceleration. We tested various kinds of stripper foils in the tests. However, great progress was not made in this problem.

Hereafter, we will proceed to the acceleration tests using the whole RIBF accelerator complex. The transmission efficiencies of ^{238}U and ^{48}Ca beams are summarized in Table 2 compared with that of ^{238}U in the previous year. Note that beam intensity monitors (Faraday cups and radial probes of the cyclotrons) include sizable errors ($\sim$20%), which is the reason why the transmission efficiencies in some sections in Table 2 exceed 100%. The transmission efficiency of the uranium beam was greatly improved as a result of the improvements mentioned above. The maximum intensity of the uranium beam delivered to the users was 0.4 pnA. In addition, single turn extractions from all the cyclotrons, except for the SRC, were also established. On the other hand, tuning of the SRC was not satisfactory and the transmission efficiency was 66%. It is a consequence of the low quality nature of the uranium beam and of poor tuning of flat-topping RF fields.

Table 2. Transmission efficiencies obtained in the acceleration tests. The RIBF accelerator complex is divided into the sections shown in the table.

Section	^{48}Ca (08/12/21)	^{238}U (08/11/16)	^{238}U (07/07/03)
IS - RILAC	55	40	29
RILAC - RRC		87	86
RRC	95	86	
RRC - fRC	/	101	41
fRC	/	87	88
fRC - IRC	/		75
RRC - IRC	106	/	/
IRC	93	86	67
IRC - SRC	88	104	72
SRC	82	66	63
Total	37	16	2

The transmission efficiency of ^{48}Ca was within the acceptable level to deliver 200-pnA beams to users. The

reason for the relatively low transmission efficiency of SRC (82%) was that one of the accelerating cavities broke down during the test and the acceleration voltage was limited to be 75% of the design value.

Detailed analyses of the acceleration tests are in progress for better performance of our accelerator complex. Using the data obtained by beam profile monitors (wire monitor) installed in the beam transport lines, we can determine parameters of beam matrices (σ-matrix) which are relevant to estimating emittances of beams under the assumption that ions obey Gaussian distributions with elliptical shapes. Figure 1 is an example of the least-square fitting of beam widths measured by the profile monitors for the ^{48}Ca beam.
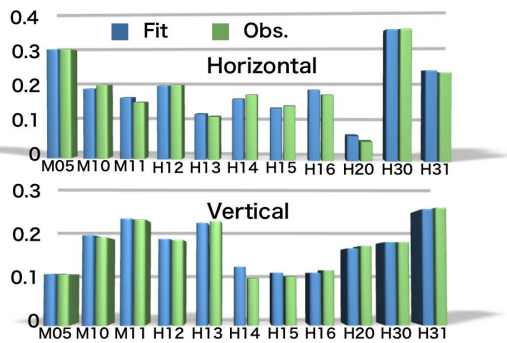
Fig. 1 Root-mean-square beam widths (cm) of the ^{48}Ca beam (08/12/21) observed in the beam tranport line from the second charge stripper to the IRC are shown compared with the fitting results based on σ-matrix analysis.

Similar analyses were done for other cases and the emittances estimated are summarized in Table 3. Note that the horizontal emittances were poorly determined compared with the vertical ones because correlation to the longitudinal motion under the presence of dipole magnets was not clearly separated due to lack of information. In that sense, the present analyses contain ambiguities, but are still useful.

Table 3 Emittances estimated by σ-matrix analyses. The emittance definition here is 4σ emittance. The unit is π mm*mrad. The abbreviations H and V stand for the horizontal and vertical direction, respectively. The horizontal emittance of ^{48}Ca in the SRC-injection beam line was too sensitive to errors in the measurement.

	^{238}U (08/11/07)		^{48}Ca (08/12/21)	
	H	V	H	V
fRC injection	5.0	2.6		
IRC injection	5 ∼ 6	2.1	2.3	2.2
SRC injection	4	1.4	1.2 ∼	1.7

For example, remarkable emittance growths in the horizontal direction are indicated in the case of uranium beam acceleration. The observed emittance growth of the fRC-injected beam originates from the mixing of the large longitudinal emittance into the horizontal one because the rebuncher[10] between RIKEN Ring Cyclotron (RRC) and

the fRC is placed in a dispersive area. The uniformities of carbon foil strippers just after RRC acceleration are poor, which result in a large momentum spread. Hence, we plan to use thinner stripper foils and accelerate 69+ ions instead of 71+ with small modifications of the fRC. Furthermore, the matching conditions on dispersion were not precisely fulfilled for both the fRC and the IRC, which resulted in additional emittance growths. The emittances of the ^{48}Ca beam were within what is acceptable.

Another example of the analyses is on turn patterns of the cyclotrons. Figure 2 shows a result of the ^{238}U beam accelerated by the IRC. Close inspection of the turn pattern helps us to reduce ambiguities in determining the horizontal emittance that is not clearly separated from the longitudinal one within the σ-matrix analyses. The horizontal emittances listed in Table 3 were determined with the help of the present turn-pattern analyses.
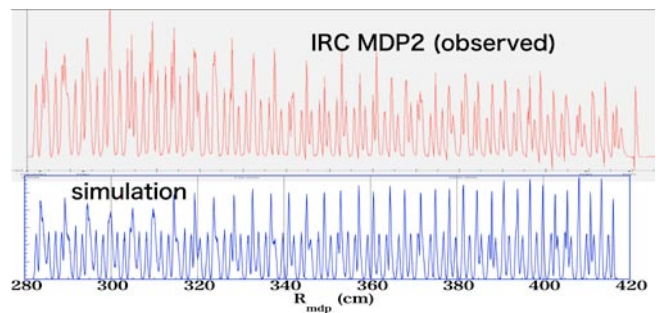
Fig. 2 IRC turn pattern of the ^{238}U beam (08/11/26) compared with a numerical simulation.

As a summary, the transmission efficiency of uranium beam acceleration was greatly improved and the ^{48}Ca beam with the maximum intensity of 170 pnA was successfully extracted from the SRC. The fact that beam losses in the beam transport lines are well suppressed enables us to carry our detailed analyses on the beam dynamic aspect of RIBF, which revealed several problems that need to be solved. We plan to fix these problems in the next fiscal year.

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Construction of the MEBT (Middle-Energy Beam Transport) line for new 28GHz Superconducting ECR Ion Source (SC- ECRIS)[†]

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The beam intensity of heavy ion must be increased for the RIBF project. J. Ohnishi, T. Nakagawa et al.[1-2] started to construct a new superconducting ECR ion source (SC-ECRIS) with an operational frequency of 28 GHz in 2007. The superconducting coils were installed in the high voltage terminal at the end of 2008. All devices will be installed by the end of March 2009.

A Middle-Energy Beam Transport (MEBT) line is being constructed for the new 28 GHz Superconducting ECR Ion Source (28GHz SC-ECRIS).[3-4] Figure 1 shows the schematic layout of the MEBT line for the 28 GHz SC-ECRIS. This beam line partly shares the existing beam line from the 18 GHz SC-ECR ion source. These magnets and the 1f-buncher/rebuncher are installed at the optimal positions of the minimum beam spots. The bending magnets (BM), quadrupole magnets (QM; DQ, TQ), steering magnets (ST), chambers, gate valves (GV), buncher and ducts used in this plan are as follows:

(1) BM; BM1, BM2 [used an injection line for the old 500 kV high voltage terminal]

(2) QM; QT011abc [from the CNS], QD012ab-022ab [from the RRC- CNS line], QDN2-1,2 [existing line]

(3) ST; SH012/SV012, SH013/SV013 [used an injection line for the old 500 kV high voltage terminal], SH03/SV03 [existing line]

(4) Chambers; Chamber011 [from the IRC line (H12a), Aluminum], Chamber012, 014 and 022 [New, Aluminum], Chamber013 and 021 [New, for CRP, stainless steel], Chamber 031 and 032 [existing line]

(5) GV; GV-011, 014 and 022 [New], GV-030, 031 [existing line]

(6) Buncher; Buncher [Modified, used an injection line for old 500kV high voltage terminal], Rebuncher [existing line]

(7) Ducts; Aluminum-Duct 10 [New, from the acceleration tube to the rebuncher], Stainless steel-duct 1 [New, from the RFQ to the rebuncher]

Fig. 1. Schematic layout of MEBT line.
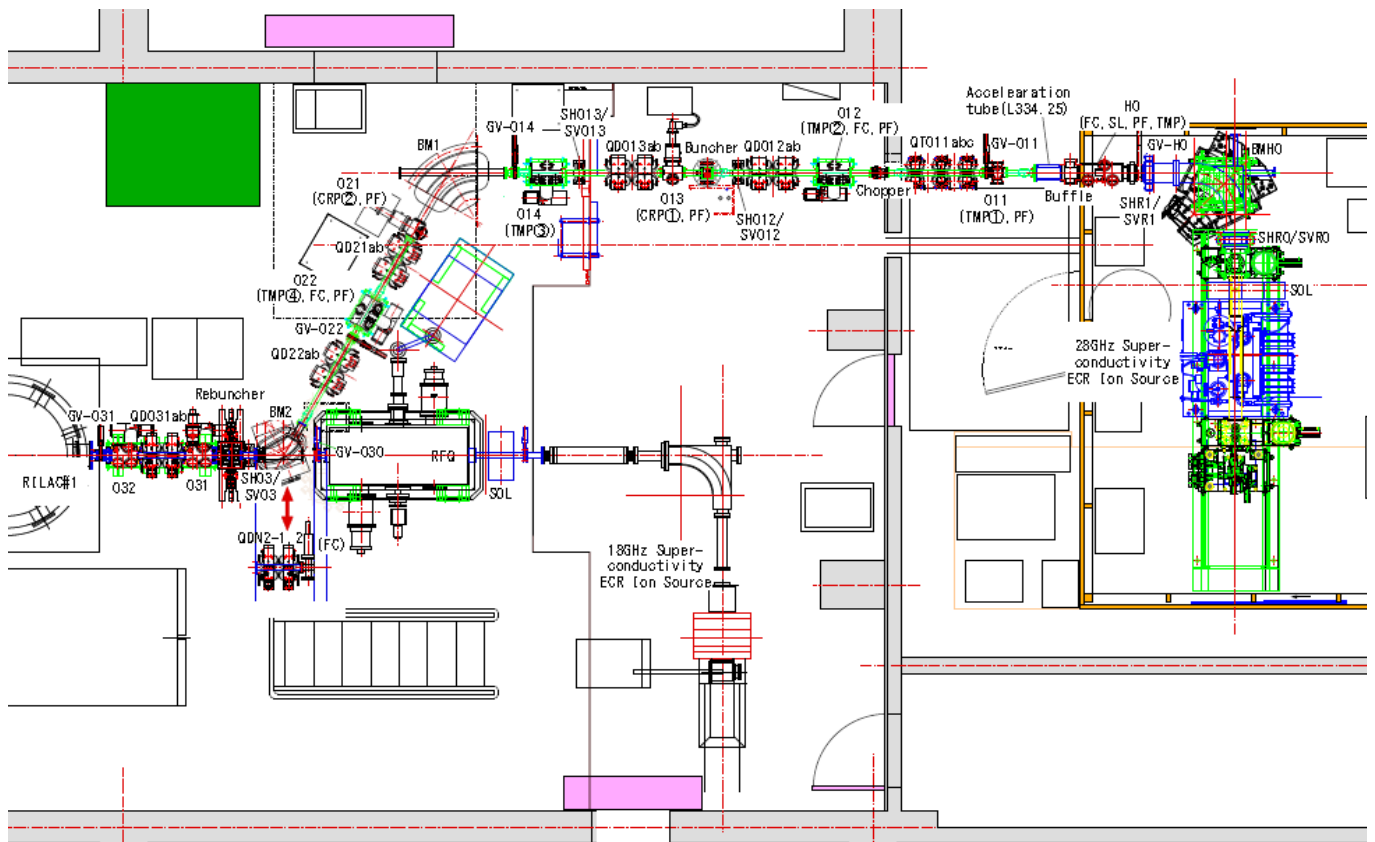
Some new bases will be constructed for the installation of these devices (QT011abc, QD012ab-022ab, QDN2-1,2, SH//SV012, 013,03, Chamber011, 013, 021, Buncher and Rebuncher). We are also planning some arrangement and works before the construction of this line as follows:

(1) Reinforcement of floor around BM1
(2) Conveyance of SC-ECR ion source and its base
(3) Arrangement of existing devices (Some operation control panels, power amplifier)
(4) Removal of the DQ from the RRC-CNS line and installation in the MEBT line.

The following are notes and points on the design of the MEBT line:

(1) Switching between the MEBT line and existing line is done simply by changing BM2 for the MEBT line and QDN2-1,2 for the existing line as shown in Figure 2.
(2) The devices, ducts and bases between the RFQ and RILAC #1 for the existing line are used as much as possible and this reduces construction of new devices, ducts, and bases.

The MEBT line will finally be installed as shown in Figure 1. We are preparing for two newly constructed chambers and bases. The main outline of the future plan is as follows:

・ ~ Feb. 2009, Final decision on the line arrangement
・ ~ May. 2009, Some arrangement and work before construction of the line
・ April ~ June 2009, Construction of the MEBT (Including cooling water, compressed air, cables and power supply)
・ July 2009~, Beam test and machine study

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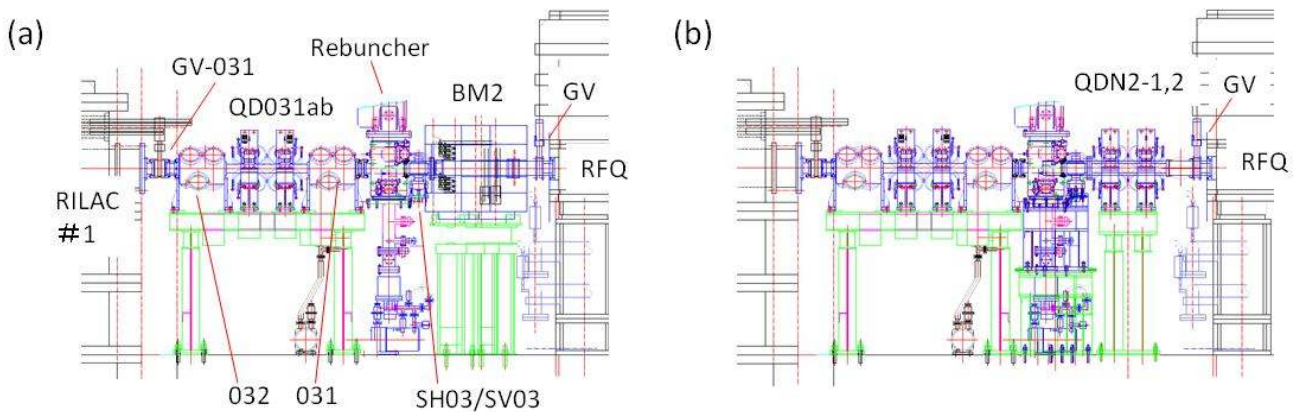
Fig. 2. Schematic layout from the RFQ to the RILAC #1. (a) MEBT line (b) Existing line.

New beam line for the AVF-RRC-SRC acceleration

K. Kumagai, N. Fukunishi, T. Maie, S. Fukuzawa*, Y. Watanabe, and M. Kase

Light ions accelerated in the AVF-RRC mode can be injected to the SRC directly because the injection radius of the SRC, 3.56 m, is the same as the extraction radius of the RRC. On the other hand, these beams cannot be accelerated in the IRC because the RRC needs to operate with a harmonic of five. In this AVF-RRC-SRC mode, the ions from deuteron to aluminum approximately can be accelerated to the maximum energy of 400 MeV per nucleon. In addition, the beams from the polarized ion source at the AVF are accelerated in the SRC.

To realize the acceleration mode, a new beam line was constructed to bypass the IRC. A schematic of this beam line is shown in Fig. 1. The beam line is from the DMH6 dipole to the DMG2. The DMH6 dipole was installed to diverge from the IRC injection beam line and two quadrupoles were moved down stream from the original positions. Part of this beam line will be used in the future to return the beams accelerated in the IRC to the experiment rooms in the Nishina building.

The beam line uses two horizontal and two vertical dipoles of 2.7 meters in radius, twenty quadrupoles and six sets of steering magnets that have both horizontal and vertical functions. The parameters of these magnets are listed in Table 1. Electric power cables for nine of the twenty quadrupoles were extended from the position of the quarupoles on the injection and extraction beam lines of the IRC that are not used simultaneously. As a result, the power

supplies can be shared and it is economical for both equipment and cabling. Though the original magnetic field rigidity of the DMM1 dipole had been small for this operation mode, it has been increased by replacing the power supply for the previous investigation of the charge stripping of the uranium beam performed.

Figure 2 shows a diagram of the designed beam envelope between the RRC-EDC and the SRC-EIC including the new beam line. An extracted beam from the RRC is matched to be achromatic after the DMM1 dipole magnet. The sections from DMH6 to DMH7 and DMH8 to DMK9 are also designed to be achromatic. The beam transferred into the SRC room is strongly focused at the position of the polarimeter installed after the quadrupole triplet QTG92. The matching condition to the SRC injection was fulfilled using the quadrupole quartette QSG22 – QSG25.

Ten profile monitors, three faraday cups and a scintillation monitor were installed in the beam line as beam diagnostic equipment. Most of these components were transferred from injection and extraction beam lines of the IRC.

The first acceleration test in the AVF-RRC-SRC mode will be scheduled in February 2009. In this test, the new beam line will be commissioned and nitrogen ions with 90 MeV per nucleon extracted from the RRC will be sent to the SRC and accelerated to the energy of 250 MeV per nucleon.
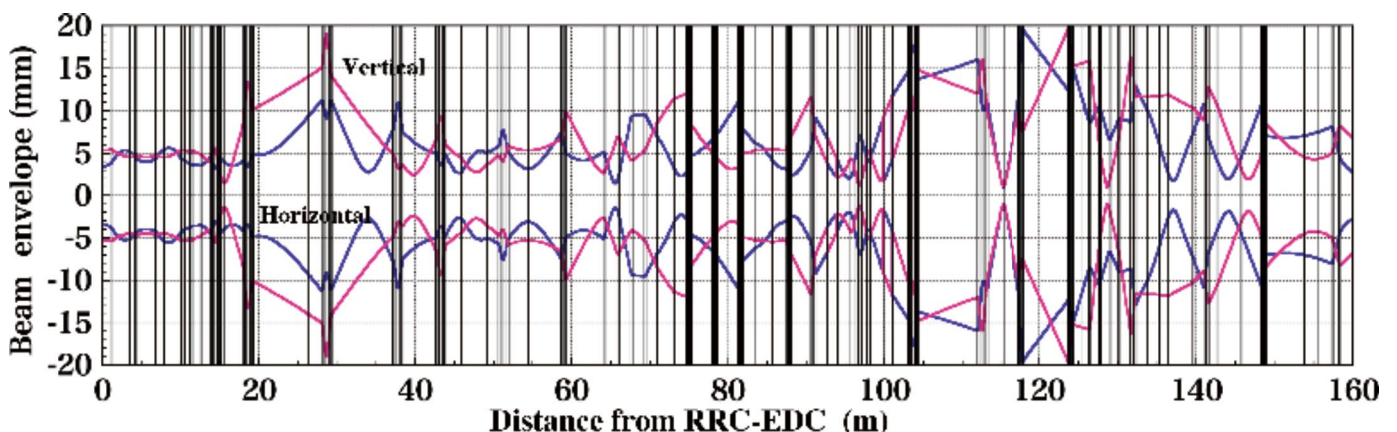
Fig.2. Beam envelope diagram. Its shows distances from RRC-EDC until SRC-EIC. New beam lines are indicated from about 71 meters to 123 meters.

	Max fields	Gap, Bore	Core length	Eff. length	Max current	Number
[unit]	[T, T/m]	[mm]	[mm]	[mm]	[A]	
Dipole 45°	1.56 [T]	60	2120.5	2149.7	330	2
Dipole 25°	1.56 [T]	60	1178.1	1206.6	330	2
Quadrupole 220	15 [T/m]	70	220	250	158	15
Quadrupole 420	15 [T/m]	70	420	450	158	5

Table 1. Design parameters of magnets used for new beam line.
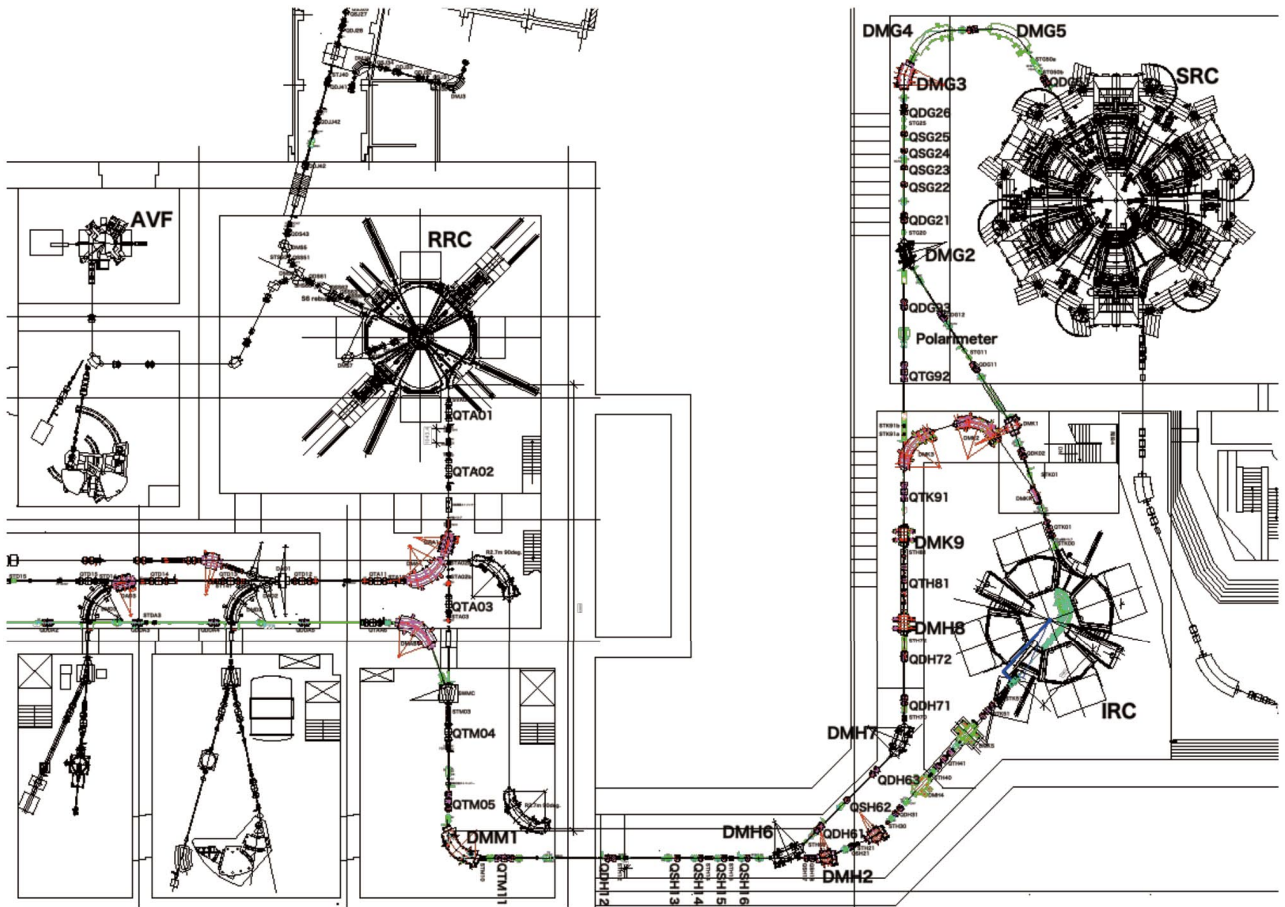
Fig.1. A schematic of beam lines from AVF-RRC to SRC.

Construction of the IRC-bypass beam transport line†

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The new acceleration mode of AVF-RRC-SRC will provide the polarized deuteron beam with energies up to 440 MeV/u as well as light ion beams, e.g. nitrogen. Experiments with this mode are planned for May 2009.[1]

For these experiments an IRC bypass beam transport line which skips the IRC was newly constructed in FY2008. This beam line partly shares the existing line which will be used for RIPS experiments in the RRC-IRC acceleration mode. Figure 1 shows photographs of the IRC bypass beam transport line after the construction. Figure 2 shows a schematic layout of the IRC bypass beam transport line.

The followings are lists of the beam line elements; dipole magnets (DM), quadrapole magnets (QM; DQ/SQ), steering magnets (ST), chambers, gate valves (GV), beam line polarimetars (Dpol, BigDpol) and ducts.

1. IRC-H zone [Fig. 1(a), (b) and Fig. 2]
  (1) DMH6 [New Chamber, a modified yoke],
     DMH7 [renamed DMH8; installed]
  (2) QSH17-18, QDH61-63, QDH71-72
     [installed]
  (3) STH14-15, STH60, STH70, STH72
     [installed]
  (4) Chamber; H16, H60, H61, H70 [New],
     H72 [from the RRC-CNS line],
     H80, H81 [New]
  (5) GV-H61 [New],
     GV-H80 [from the RRC-CNS line]
  (6) Al-Duct; 12 [New]

2. IRC-K zone [Fig. 1(b) and Fig. 2]
  (1) DMK9, DMK3 [installed]
  (2) QDK91 [installed]
  (3) STH91ab [from the RRC-CNS line]
  (4) Chamber; K90 [modified],
     K91 [from the RRC-CNS line]
  (5) GV-K91 [from the RRC-CNS line]
  (6) Beam line polarimeter, BigDpol
  (7) Al-Duct; 8 [New]

3. SRC-G zone [Fig. 1(c) and Fig. 2]
  (1) QTG92, QDG93 [installed]
  (2) Chamber; G93 [from the RRC-CNS line]
  (3) Beam line Polarimeter, Dpol
  (4) GV-G93 [from the RRC-CNS line]
  (6) Al-Duct; 4 [New]

The beam line polarimeters, Dpol and BigDpol, were installed at positions where beam size becomes small. The Faraday cups (FC) and profile (PF) monitors have been

(a)

(b)

(c)
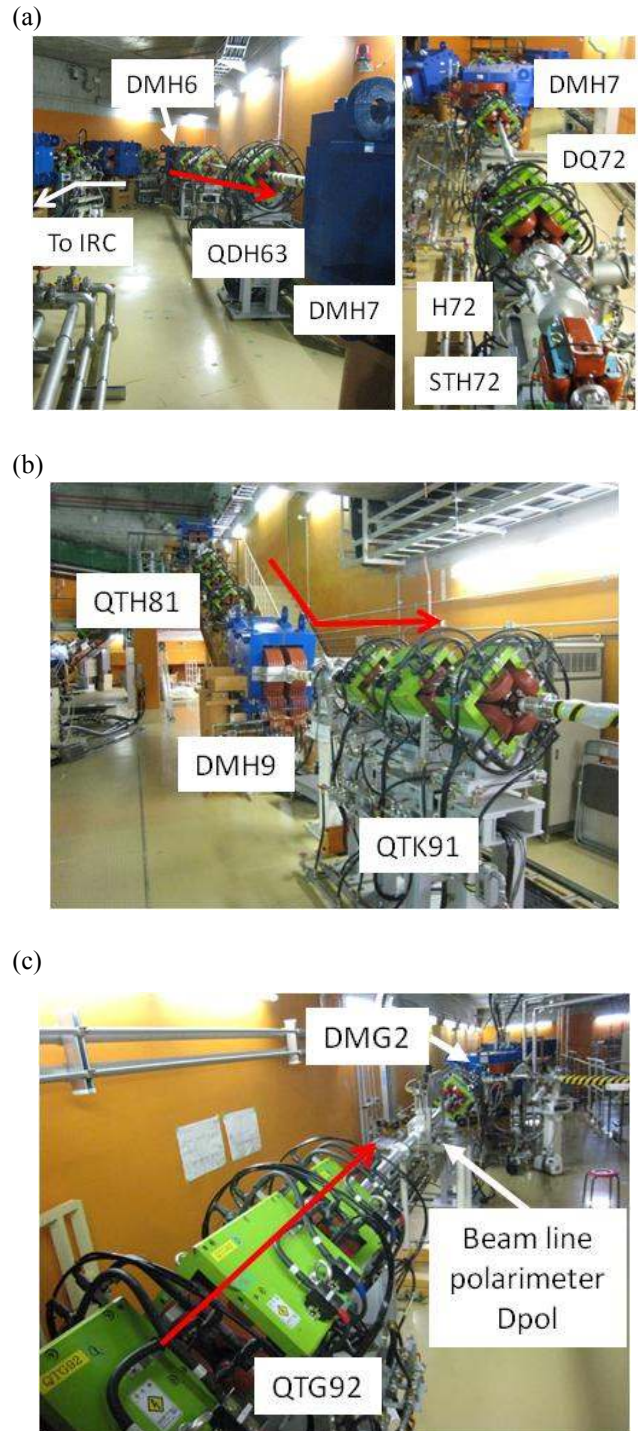
Fig. 1. Photographs of the IRC bypass beam transport line after arrangement. (a) IRC-H zone (b) IRC-H and K zone (c) SRC-G zone.

relocated from the skipped beam line in the IRC and SRC rooms. Because the dipole magnet DMH6 is used in both the IRC line and the IRC bypass beam transport line, we have made the following modifications. The upper yoke was removed and converted, and a chamber with branched flanges was newly constructed. Quadrapole magnets DQ/SQ were disassembled in order to install the Al-ducts. Alignment (Y level, pitching direction and yawing direction) of DM, QS/QD and the chamber was performed with precision of less than 0.1 mm in each straight line section.

Experiments using the new beam line will be performed after acceleration tests. We plan to conduct acceleration tests in AVF-RRC-SRC mode in Feb. 2009 and machine studies in May 2009.

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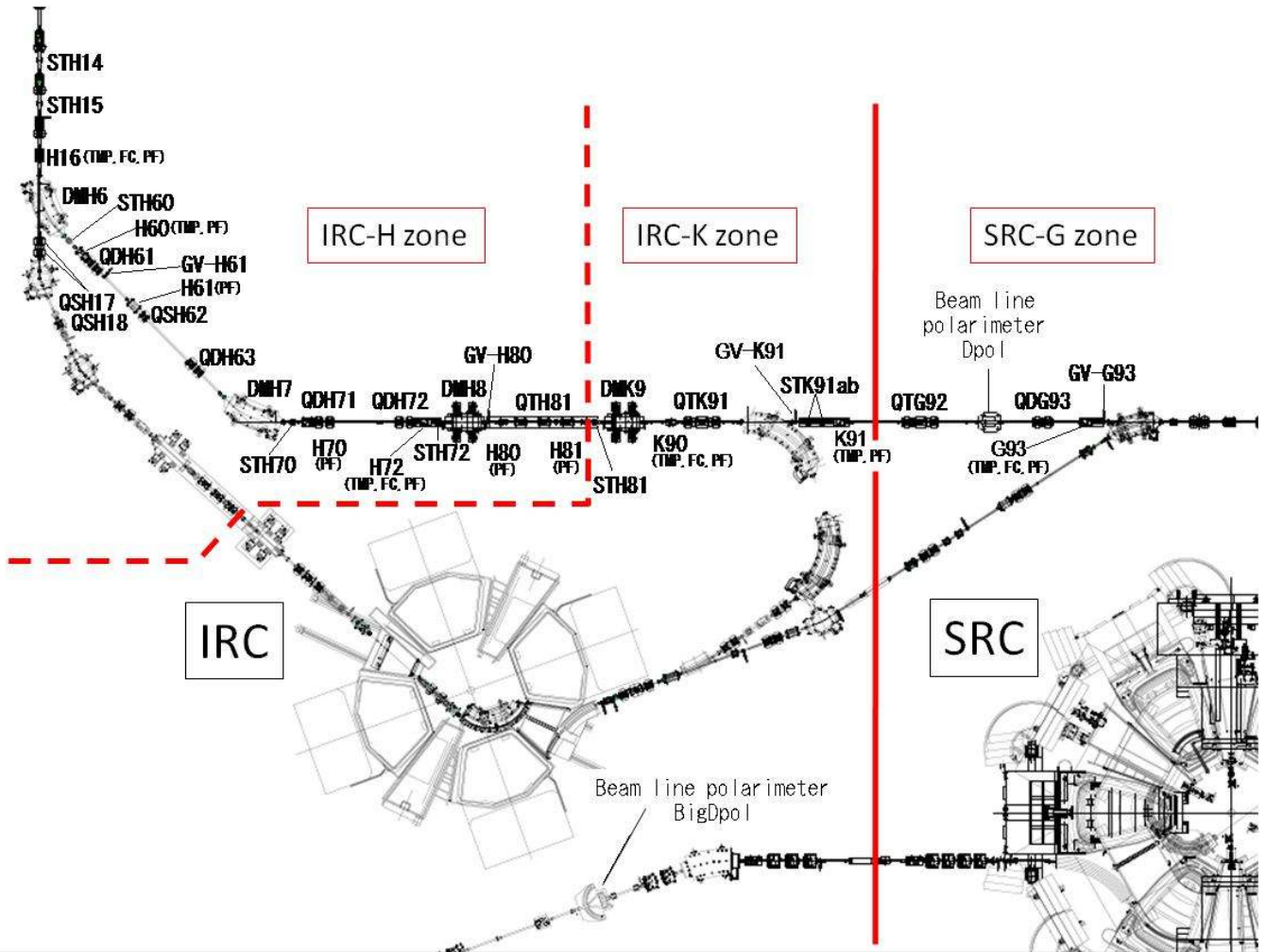
Fig. 2. Schematic layout of IRC bypass beam transport line.

Refinement of SRC for acceleration of high intensity beam in 2008

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The source of the problem in the SRC cryogenic system was found to be the contamination of the lubricant oil from screw compressors passing through the cascade of oil separators.[1] The oil polluted the entire refrigerator. Consequently, the SRC was shutdown until August 2008 to rinse out the impurity. During the repair of the cryogenic system, various modifications were introduced to the SRC. The re-cooldown of the SRC started in September and the superconducting coils were ready to operate in October. The acceleration of ^{238}U was performed immediately for the commissioning of the Zero-Degree Spectrometer and following new isotope search in November. Maximum beam intensity of 0.4 pnA was achieved, which was ten times higher than the one in 2007. Following that, the first acceleration of ^{48}Ca for the SRC was performed in December. The modifications and elaborate tuning of accelerators realized the world's most intense ^{48}Ca beam that reached up to 200 pnA on the Faraday cup located at the exit of the SRC. The details of modification and status for the SRC in 2008 are presented as follows.

for the adjustment of RF. The radial beam pattern is measured by a differential electrode (the SRC has differential electrodes divided by three) mounted on behind an integral electrode with 0.5 mm overhang. Only the beam reaching the "0.5 mm" is counted at each radius. However, a lot of secondary electrons emitted from the MDP integral electrode had a great influence on the observation and the pattern could not be produced.[2] In order to overcome the problem, a new differential electrode of 0.3 mm×3 mm tungsten ribbon was attached in front of the integral electrode at intervals of 10 mm as shown in Figure 1.
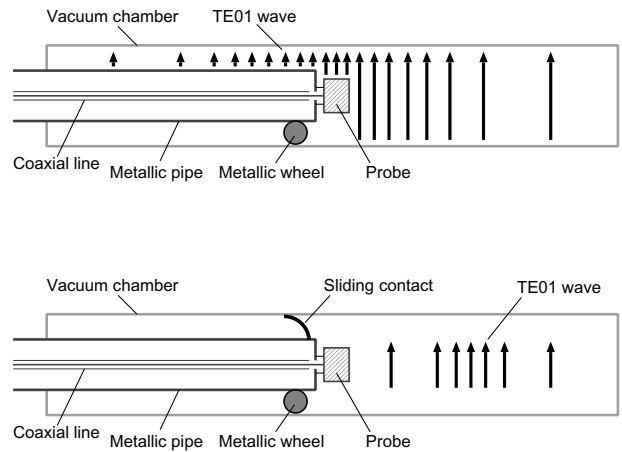
Fig. 2. Effect to disturb the propagation of TE01 microwave.

Fig. 1. Head assembly of the main differential probe mounted on SRC.

In order to improve the transmission efficiency of the SRC, a correct adjustment of RF voltage and phase is required, especially for flat-top acceleration cavity (FT). The goal is to observe proper information from the radial beam pattern by using the main differential probe (MDP) because the information gives a criterion

Fig. 3. Cross sectional view of the pantograph system for sliding contact.

Another problem we had in the MDP was that the beam signal was disturbed by the electromagnetic radiation from the FT resonator: the rf frequency is high enough for the electromagnetic wave to travel through the vacuum chamber. A schematic drawing of the

MDP in the chamber is shown in Figure 2. The driving shaft of the MDP is grounded by the metallic wheel on the chamber in the original configuration. Since the electromagnetic wave is TE01 mode, this asymmetric configuration allows the electric field to penetrate into the narrow gap between the shaft and the chamber, which induces the electric charge in the head of the probe. Therefore, we put an electric contact on the upper side of the shaft, as shown in Figure 2, in order to suppress the electric field around the probe head. A pantograph structure as illustrated in Figure 3 was adopted because the chamber face was not seamless. An adjustment for balance of the vertically located movable shorts in the FT is required simultaneously in order to reduce the leakage of microwaves. These modifications enabled us to measure the radial beam pattern for the entire region of the MDP with using the FT resonator as shown in Figure 4. Note that the low-level circuits of all RFs for the SRC were adjusted to stabilize the voltage and phase of resonators.[3].
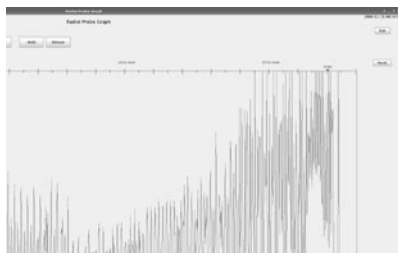
Fig. 4. Radial beam pattern of SRC for ^{48}Ca beam in December 2008.

In the most cases, the major beam loss in cyclotron takes place on the septum of electrostatic deflector (EDC). For the acceleration of kilowatt beams, machine protection is required in order to avoid serious thermal damage caused by the large beam loss. For the protection during ^{48}Ca beam acceleration, ten Type-E thermocouple gauges with ceramic tubes were mounted on the EDC septum to measure the temperature and switch off the beam if the maximum heat-up exceeded the criterion, which was set as 5 degrees in December 2008. This EDC protection worked well for the ^{48}Ca beam. The temperature clearly responded to the beam loss and the extraction efficiency could be improved via tuning such as decreasing the temperature. Note that the temperature of EDC septum is also useful to us for adjusting the balance of the FT resonator because the temperature increases depending on the amount of RF leakage.

Additionally, several modifications were made to make maintenance easier, described as follows. Profile monitors (PF-SV1, SV2) mounted on the vacuum chamber of valley were converted to setback, so as not to block the detachment of EIC and EDC. Many

scaffolds were placed round in the SRC for the access to RF resonators when the magnetic shielding doors were closed. The mounting direction of a gate valve for assist-pumping TMP on the resonator no.2 was retouched for easy access to the maintenance hatch.

Several problems occurred on the SRC in 2008, described as follows. The vacuum pressure was degraded when the high RF power was fed to the resonator. It was found that the temperature of cryopump was rose remarkably due to the extreme heating up of the RF shield attached in front of the pump due to RF irradiation.[4] The problem was solved by mounting a water-cooling thermal baffle[5] on the RF shield. Magnetic shields were covered on all cryopumps to prevent the degradation of performance from a stray field. The shaft of MDP emitted a loud noise and was scraped by its plain bearing. The bearing will be replaced to a roller type in March while the outer vacuum-duct of MDP will be modified to bellows for quick access to the head assembly. The angle settings of EDC, which determine the radius of curvature for beam extraction, were mechanically slid around the drive shaft, and we were not able to extract the uranium beam in a whole day until we readjusted them. The driving screw of EDC "α"-axis was cleaned and lubricated because it had hardened and was not able to drive. A directional coupler on the power feeding line of the RF resonator no.2 was burnt due to the excitation of third-harmonic mode. The contact fingers of the coarse tuning panel in the RF resonator no.3 burned out during the ^{48}Ca experiment as a result of insufficient contact pressure because the shaft of the panel was not eccentric. The directional coupler in the wide-band driver amp of the FT resonator had the problem of a wire breaking.

A new beam acceleration scheme of AVF-RRC-SRC with IRC bypass beam line[6] is scheduled for the spring of 2009 to perform the commissioning of SHARAQ and some experiments using 250 MeV/u ^{14}N or 250 MeV/u polarized deuteron beam. An acceleration study for the ^{14}N beam was performed from February 5th to 9th. Additional beam diagnosis elements will be mounted on the SRC at the end of March because the existing elements cannot stop the deuteron beam.

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Completion of Superconducting Magnet for the 28 GHz ECR Ion Source

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The superconducting magnet for the 28 GHz ECR ion source, under construction at a factory of the Mitsubishi Corporation since October 2007, was completed in December 2008. It consists of six solenoids SL1~SL6 and a set of sextupole coils as shown in Fig. 1. The maximum axial magnetic fields are 3.8 T on the RF injection side and 2.2 T on the beam extraction side. The sextupole magnetic field is approximately 2.2 T on the inner surface of the plasma chamber (r = 75 mm). The radius of the room temperature bore is 86 mm. The coils use a NbTi-copper conductor and are bath-cooled in liquid helium. The maximum magnetic fields on the SL1 and the sextupole coils are 7.2 T and 7.4 T, respectively. The design details of the superconducting coils are described in Ref. 1 and 2.

The coil winding began in January 2008. The SL3 and SL4 use a conductor with a round shape of ϕ1.09 mm and a copper/NbTi ratio of 6.5, while the other solenoids and the sextupole use a conductor with a rectangular shape of 0.82 mm x 1.15 mm and a copper/NbTi ratio of 1.3. Each of the six sextupole coils was dry-wound to work for turn

transitions and was vacuum impregnated with epoxy. The percolation of the epoxy into the inside of the windings was inspected and found to be successful by cutting a trial winding. On the other hand, each solenoid coil was wet-wound with warm epoxy and cured.

The six sextupole coils need to be fixed tightly because they are subjected to large magnetic forces from the solenoids. Figure 2 shows a cross section of the straight part of the sextupole between the SL1 and SL2. The six sextupole coils are assembled using titanium spacers with a triangular cross section and fixed with four layers of ϕ0.65 mm stainless steel wires wound with very high tension of about 580 MPa. An iron pole of 330 mm in length is inserted in the central region of each coil to increase the sextupole field. A stainless steel disk with outer diameter of 250 mm and a thickness of 30 mm is inserted between the SL1 and the SL2 to fix the sextupole coils more tightly because the magnetic force in the azimuth direction is strongest there. The mechanical design here was carried out[2] by combining 3D magnetic force calculation with Opera3D[3] and mechanical calculation with ANSYS.[4]

The final assembly of the sextupole coils and six solenoids is shown in Fig. 3. The ends of the sextupole coils are fixed with a stainless steel ring to support the large radial magnetic force acting on the current return sections. The six solenoids were assembled with stainless steel spacers and tightened with sixty-four long aluminum-alloy bolts that support a maximum repulsive force of approximately 800 kN among them.

Excitation tests of the completed coils were carried out in a commonly used cryostat in June 2008. First, the solenoids were tested one by one and all achieved the design currents without a quench. Next, the sextupole was tested. Table 1 shows the currents when a quench occurred in the sextupole.
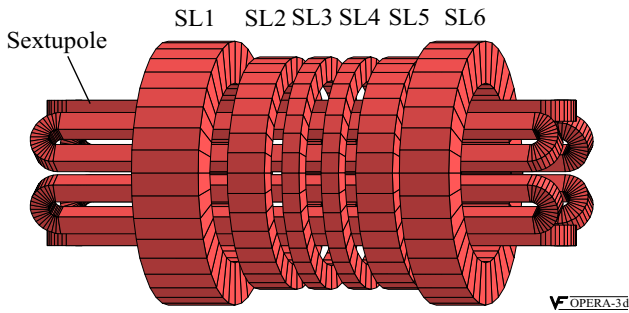
Fig. 1. Arrangement of the superconducting solenoid and sextupole coils.
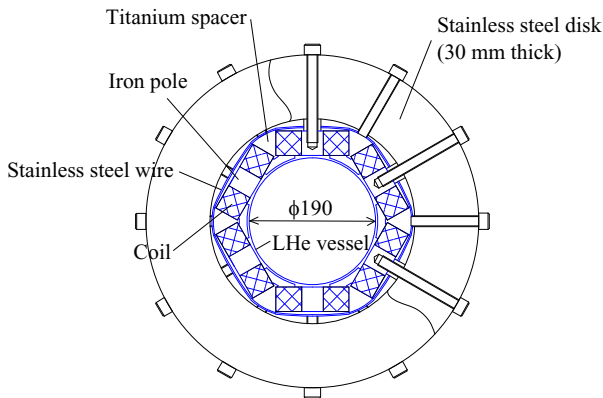
Fig. 2. Cross section of the straight part of the sextupole coils. A 30 mm thick stainless steel disk is inserted between the SL1 and the SL2.
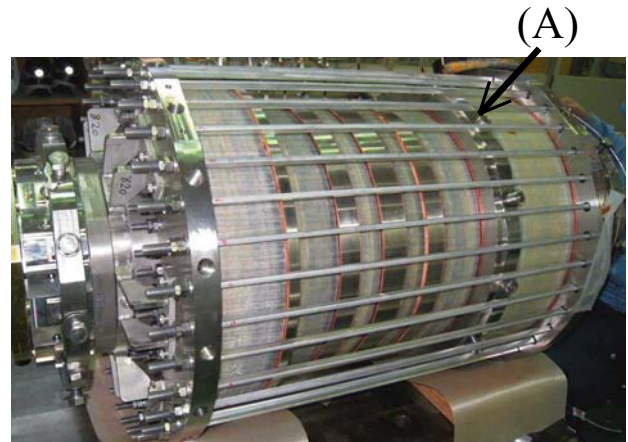
Fig. 3. Photograph of the coil assembly. (A) is a 30 mm thick stainless steel disk inserted between the SL1 and the SL2.

Table 1. Coil currents (Amps) when the sextupole quenched.

run #	sextupole	SL1	SL2	SL5	SL6
design	272	162	182	155	132
1	189				
2	255				
3	90	136	183		
4	65	136	183		
5	73	136	183		
6	114	136	183		
7	70	136	183		
8	77	136			
9	109				132
10	220				92
11	204			155	132
12	230			132	112
13(NQ)	272				
14	258	146	164		
15	234			135	114
16	238			136	116
17	235	127	143		

The sextupole also achieved the design current (271 A) after two quenches (189 A, 255 A) when no solenoids were excited. In all cases where the sextupole and one or two of the solenoids were excited at the same time, the sextupole quenched. The sextupole quenched at low currents ranging from 65 A (24%) to 115 A (42%) when SL1 and SL2 were excited at their design currents in advance (run #3-#7). The sextupole also quenched in a similar way when the SL6 was excited in advance (run #9, #11). The cause of these quenches was presumed to be coil motion at the ends of the sextupole, due to the voltage signals observed in some of these runs. In run #10, the SL6 was ramped after the sextupole was excited at 220 A. In run #12 and #14-#17, the solenoids and the sextupole were excited simultaneously, keeping a ratio of the currents so that the direction of the force acting on the sextupole coils did not change during the excitation. The quench current of the sextupole increased to more than 85% of the design value in this way. It was, however, difficult to reach the design current.

The results of these tests suggested that the support structure at the ends of the sextupole coils is not strong enough against the radial force toward the centre. Methods of remedying this problem were investigated, and performance was improved by increasing the thickness of the inside wall of the helium vessel for room temperature bore at both ends (see Fig. 2) and pressing the end parts of the sextupole coils against those points. After four months, we successfully achieved excitation of all the solenoids and the sextupole at the design currents after the sextupole quenched twice at current levels of 96% and 98%.

After this second excitation test, the cryostat for the 28 GHz ECR ion source was assembled with the superconducting coils in a short period of time and completed in December 2008. A photograph of the completed whole magnet is shown in Fig. 4. The cryostat is surrounded by yokes with thicknesses of 50 mm and 80 mm. Three cryocoolers (Sumitomo Heavy Industries) with two cooling stages each are installed at the top of the cryostat to

Fig. 4. Photograph of the completed superconducting magnet for the 28 GHz ECR ion source.

Table 2. Heat leak, capacity of the cryocoolers, and measured temperature at the stages of liquid helium and two radiation shields.

	LHe vessel	Inner shield	Outer shield
Heat leak (design)	0.14W@4.2K	18W@40K	127W@70K
RDK408D2	1W@4.2K		43W@45K
RDK408S x 2		18W@12K	86W@52K
Temperature (measured)*	4.2K**	14K	47K

*Cryocoolers operated at 60 Hz.
**Heater was powered at 1.2W to keep He pressure positive.

maintain approximately 330 liters of liquid helium. One (type RDK408D2) is used for re-condensing the liquid helium and cooling the outer of two radiation shields, and the other two (type RDK408S) are used for cooling of the inner and outer radiation shields. Nine current leads use high Tc superconducting material between the liquid helium vessel and the inner shield to reduce the heat leak to the liquid helium temperature. The designed values of the heat leak and capacity of these cryocoolers are listed in Table 2.

The magnet and cryostat were cooled down and tested. It took 1.5 days for pre-cooling with liquid nitrogen and pouring of liquid helium. The temperatures of the radiation shields in the steady state with the cryocoolers operating are listed in Table 2. The capacity of the cryocoolers was found to have a sufficient margin because the temperatures were lower than expected. The superconducting coils were excited again at the design currents after the sextupole coil had quenched once at the 96% current level.

After the operation test, the cryostat and magnet were warmed up and carried to RIKEN on December 19, 2008. The ion source of this magnet will start to operate in the spring of 2009.

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Production of highly charged Na ion beams from the RIKEN 18 GHz ECRIS

Y. Higurashi, T. Nakagawa, M. Kidera, T. Aihara, M. Tamura, M. Kase , A. Goto and O. Kamigaito

In a series of experiments to search for super-heavy elementin this case to verify the elemant with an atomic number of 113), an intense beam of Na ions was strongly needed at the end of 2008. The requirement was to produce an intense beam (~4pμA) of ^{23}Na ions as long as possible , with no break, in order to minimize experiment time. To meet this requirement, we conduced a test experiment to produce Na ions, and supplied an Na^{7+} beam for the experiment.

Toproduce the Na beam, we used NaF rod (4x4x35mm^3). The NaF rod was directly inserted into the ECR plasma of RIKEN 18 GHz ECRIS and heated up to obtain sufficient vapour pressure. The description and performance of the RIKEN 18 GHz ECRIS are reported in Ref.1.

Figure 1 shows the charge distribution of an Na ions. The ion source was tuned to produce Na^{7+} ion beam. The RF power was 300W. The gas pressure was 5x10^{-7}Torrs. The extraction voltage was set to 11.7 kV. In this experiment, we used He gas as an ionized gas.   Figure 2 shows the beam intensity of Na^{7+} as a function of RF power. The beam intensity increased as RF power was raised to 48 eμA.

mg. It is estimated that the consumption rate in this experiment was ~0.4 mg/h. The total weight of the rod is ~1.2 g. This means that, in principle, we can produce Na ions for 3000 h without inserting an additional rod.
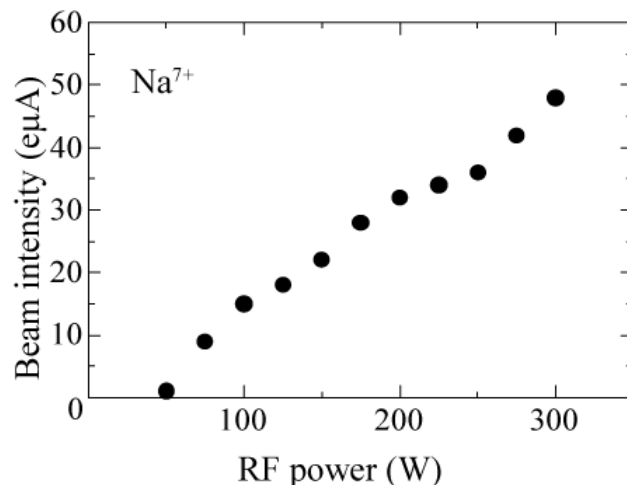
Fig. 2. Beam intensity of Na^{7+} ions as a function of RF power.

Fig. 1. Charge distribution of Na ions. The ion source was tuned for production of Na^{7+}.
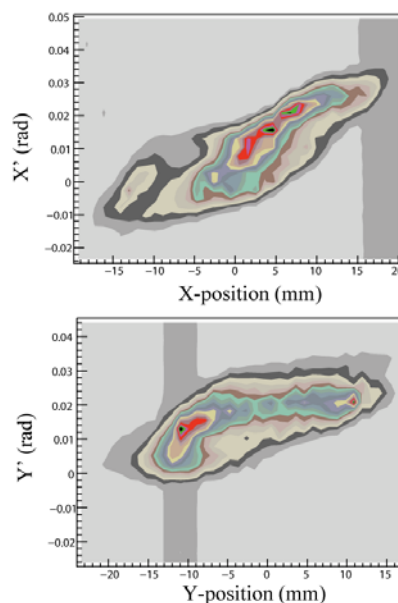
Fig.3. x and y emittance of the Na^{7+} ion beam.

Figure 3 shows the 99% x and y-emittance of the Na^{7+} beam under the same conditions for production of 48 eμA Na^{7+} beam.   The x and y emittance were 265 and 262 πmm・mrad, respectively.

Using this method, we successfully produced an average beam intensity of 45 eμA for 30 days for the experiment without any break. The total consumption of NaF was ~300

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Production of a highly charged Ge beam form the RIKEN 18 GHz ECRIS

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Recently, an intense ^{76}Ge beam was strongly needed to search for a super-heavy element (atomic number 114) at RIKEN after producing the element which has an atomic number of 113.[1] The requirement of this experiment was to produce an intense beam (1~2 pμA) of ^{76}Ge^{17+} ions as long as possible without break in order to minimize breaks in the experimental time. This is because the estimated cross section is very small (smaller than pb(10^{-36} cm^2)).

One popular methods for producing highly charged heavy ions from a solid material is to use the oven in the plasma chamber of the ECR ion source[2]. Using this method one can produce an intense beam of highly charged heavy ions at a low consumption rate (lower than 1mg/h). However the main drawback of this technique is the limit on the material volume (~several 100 mg) which can be contained in the oven at present, when we install the oven in the small plasma chamber. If we assume a consumption rate of 1mg/h, the duration of the beam supply is several 100 h.

temperature.[3] The advantage is that one can produce metallic ions in the same way as ion production with gaseous elements. This means that we can produce highly charged metallic ions for a very long period, without any break, if we can find a proper material for the MIVOC method.

For these reasons, we chose the MIVOC method for production of Ge ions. For production of Ge ions, we used trimethylgermanium ((CH_3)$_3$GeH) which has a high vapor pressure (~several 100 torr) at room temperature.

Description and performance of the RIKEN 18 GHz ECR ion source are described in Ref. 4. Figure 1 shows a cross sectional view of the ion source and the microwave injection side. The material was placed in a chamber connected to the ECR plasma chamber by a gas-feeding tube via a variable leak valve. The gas flow rate was controlled by the variable leak valve. The inner wall of the

RIKEN 18 GHz ECR ion source
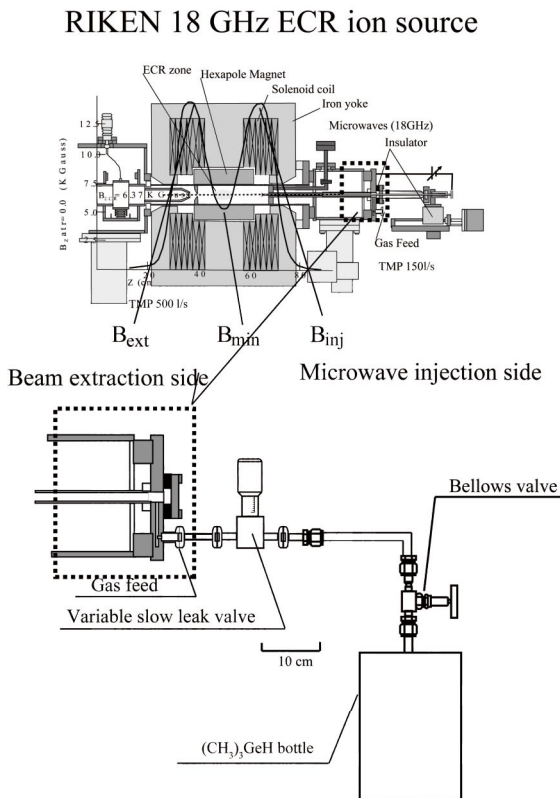
Fig. 1 Schematic drawing of the RIKEN 18 GHz.

A MIVOC method for the ECR ion source enables production of highly charged metal ions at room

Fig. 2. Charge state distribution of Ge ions.
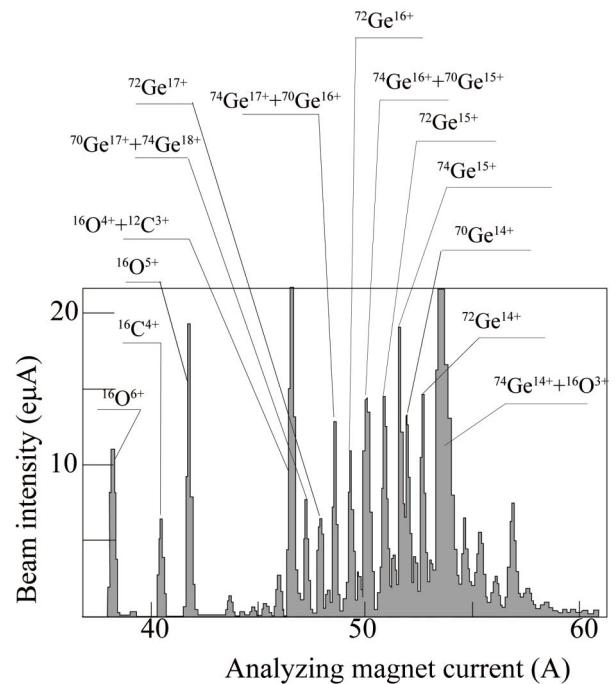
plasma chamber was covered by a thin aluminum cylinder (1mm thickness).[5]

Figure 2 shows the charge state distribution of the Ge ions. The RF power was 500 W. The gas pressure was 8x10^{-7} Torr. The maximum magnetic field strength on the microwave injection side, the minimum strength of the

mirror magnetic field, and the maximum magnetic field strength on the beam extraction side were 1.4, 0.49 and 1.2 T, respectively. The extraction voltage was 10 kV. Before producing Ge ions, we cleaned the inner wall of the aluminum cylinder whith an oxygen plasma for 2 days.To stabilizethe beam intensity we had to supply oxygen gas as a support gas. When adding the oxygen gas as a support gas, the beam intensity was very stable. Instability of beam intensity was within few %. As shown in Fig. 2, the charge distribution of Ge ions is very complicated, due to the existence of many kinds of stable isotopes (^{70}Ge, ^{72}Ge, ^{73}Ge, ^{74}Ge and ^{76}Ge).   The isotope ratio of ^{70}Ge, ^{72}Ge, ^{73}Ge, ^{74}Ge and ^{76}Ge are 21, 27, 7.7, 36 and 7.6%, respectively. To estimate the beam intensity for each charge state, we chose the beam intensity of ^{73}Ge, because only ^{73}Ge was present in the one peak in the charge distribution. Based on these results, the beam intensity of highly charged Ge ions is estimated as shown in Fig. 3.
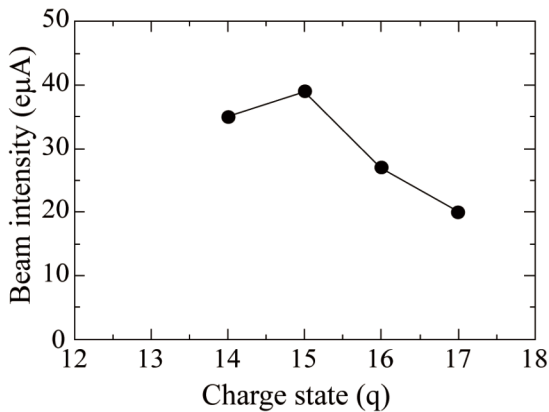
Fig. 3. Beam intensity of highly charged Ge ions.

Figure 4 shows the beam intensity of ^{72}Ge^{17+} and ^{76}Ge^{18+} as a function of RF power. It is estimated that 80% of the intensity of the ^{72}Ge^{17+} and ^{76}Ge^{18+} ion beam is ^{72}Ge^{17+}. The beam intensity increases with increasing RF power. Figure 5 shows the beam intensity as a function of bias disc voltage.
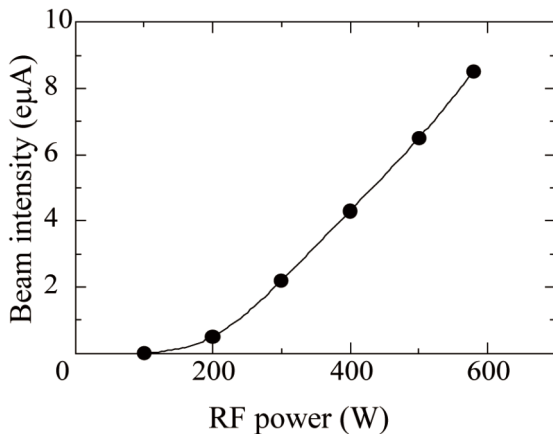
Fig. 4. Beam intensity of ^{72}Ge^{17+} $^{+76}$Ge^{18+} ions as a function of RF power.

In conclusion, we successfully obtained higher than 1pμA of Ge^{17+} with the MIVOC method. This will be used for a super-heavy element (Z= 114) search experiment after producing (CH$_3$)$_3$^{76}GeH. In this experiment, we used a slit width of 8 mm, which is placed in front of the faraday cup. When using (CH$_3$)$_3$^{76}GeH, we can use a wider slit width (~40mm) because we do not need such good mass resolution. In this case, we may obtain higher intensity than with slit a width of 8mm.

Fig. 5. Beam intensity of ^{72}Ge^{17+} $^{+76}$Ge^{18+} ions as a

function of negatively bias disc voltage.
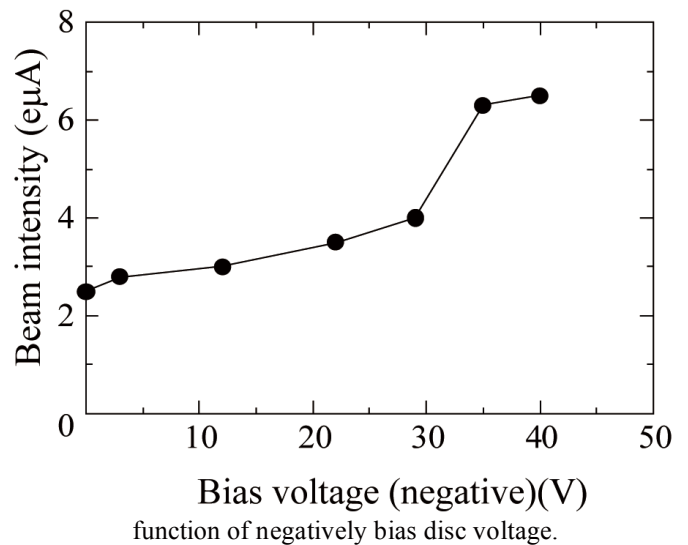
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Improvement of rf-system for cyclotrons at RIBF

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Improvements have been made to make the rf field much more stable and make the system itself much reliable. Deviations of the amplitude and phase of the acceleration voltage are required to be $\pm 1 \times 10^{-1}$ and $\pm 0.05°$, respectively. Stability of the voltage and the phase of acceleration field of rf cavities is one of the most important issues for reliable operation of cyclotrons. An unstable rf field causes emittance growth of the beams during acceleration because energy gain per turn varies according to the rf field deviations, and the radius of the beam orbit changes, resulting in beam losses especially at the extraction device. Stable rf means not only constant amplitude and locked phase with reference to the rf signal from the master oscillator but also minimum interruption to providing beams due to rf breakdown which occurs due to sparks on the cavity surface.

The unstable of the rf field can be categorized into modulation and drift. Modulations of voltage and phase are caused mainly by ripple in the d.c. power supplies of amplifiers. Power supply ripples have main frequency components of 300 Hz and appear as an amplitude modulation and a phase modulation with a frequency of 300 Hz. Modulation of the rf signal can be observed as a side-band spectrum by using a spectrum analyzer. For example, an amplitude modulation of $\pm 5 \times 10^{-4}$ and a phase modulation of $\pm 0.1°$ correspond to spectrum levels of -72 dBc and -61 dBc, respectively. This modulation will be removed/minimized

by tuning a feed-back loop (i.e., choosing a gain and a time constant) while observing strength of the side-band spectrum. After careful tuning of the feedback loop the sideband of 300 Hz ripple was reduced to -76 dBc.

On the other hand, drift of the rf voltage and phase occurs due to change in atmosphere temperature and change power supply. The temperature control oven system is equipped for the feed-back control. The temperature of the oven is controlled within $|\Delta T| < 0.5°C$. In addition, an automatic voltage regulated power supply was introduced to the Auto Gain Control and Phase Lock Loop.

Finally the stability shown in Fig. 1 was achieved. Phase drift of only $0.05°$ of RES3 was observed over 14 hours. The others were well stabilized within 0.1% and $0.1°$. Fig. 1 plots records of the amplitude and phase of 4 acceleration and 1 flattop cavities of the SRC during acceleration of ^{14}N with an energy of 250 MeV/u (f = 27.4 MHz). The gap voltage/rf power of acceleration cavities (RES1~4) and flattop cavity (FT) of the SRC were 440 kV/100 kW and 200 kV/12 kW, respectively. The measurements were made by using a new rf-monitor system.[1] While the old vector voltmeter system had resolutions of 0.1 % and $0.1°$, the voltage and phase resolutions of the new monitor are 0.01 % and $0.02°$, respectively.

In the case of rf voltage control breakdown due to a spark, it is important to recover rf voltage as soon as possible, otherwise it takes more than half an hour to manually recover by adjusting tuner a few cm, due to thermal deformation of the cavity by a cooling water.

The low level system has an automatic recovery mode which turns the rf input to the rf amplifier into
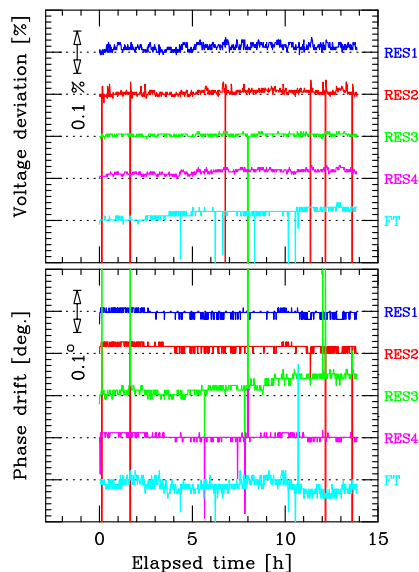
Fig. 1. Measured voltage(upper) and phase(lower) of cavities for SRC at the frequency of 27.4 MHz.
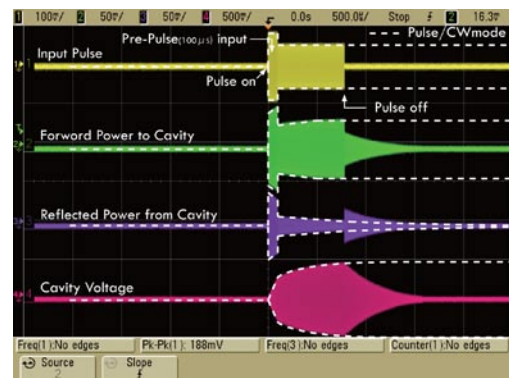
Fig. 2. Pre-pulse is introduced to pulse-mode to overcome multipactor of the cavity. a) envelope of input signal to amplifier. b),c) forward and reflected power at coaxial feeder line, respectively. d)pickup signal of cavity.

pulse mode. The pulse mode has very fast $\Delta V/\Delta t$ of a few μs, and is crucial for overcoming the multipactor of the cavity in the recovery process. The rise-time of the cavity voltage is defined by the cavity and amplifier response. Therefore, in order to obtain fast pulse, large amplitude pre-pulse with a length of 100 μs is introduced to the normal pulse to obtain a fast pulse. Fig. 2 shows the envelopes of the input pulse, forwarded power, reflected power and cavity pickup signal. It has been found that the fast $\Delta V/\Delta t$ pulse successfully overcome the multipactor with a pre-pulse and consequently restores normal power to the safe level for power supplies of amplifier and the cavity itself. In automatic-recovery mode, the cavity voltage will be recovered along the dashed line within a few ms. Therefore no voltage down of RES4 was observed during the stability measurements shown in Fig. 1. It may be concluded that the pre-pulse excitation works very well. Fine tuning of the amplitude and length of the pre-pulse is in progress.

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Stability of RF system at RILAC in RIBF

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The accelerating RF system of RILAC which is an injector to RRC in RIBF, must be highly stable as well as the four cyclotrons located downstream for a long term such as several weeks in order for us to provide high intensity heavy ion beams up to 1 pμA. If we maintain a deviation of beam phase before injection to RRC within ± 1° of accelerating RF of RRC, corresponding to 152 ps for ^{48}Ca case (=2/36.5 MHz/360 deg.), it is required to achieve RF stability of ± 0.1% in voltage and ± 0.1° in phase, since the coefficients of beam phase against RF of RILAC before injection to RRC are typically 0.5 – 1.0 nsec/% in voltage and 0.5 nsec/% in phase. For the purpose of determining the degree of stability, the RF voltage and phase were monitored as well as beam magnitude and phase using lock-in amplifiers (LIA) during the beam time of RIBF[1]. Fig. 1 shows the long-term deviation of RF pickup voltages and phases in six tanks of RILAC observed during Uranium acceleration (f=18.25 MHz) in July 2008. The voltages for the last two tanks (#5 and #6) are rather stable within 0.05%, whereas that for the tanks #1 – #4 deviate more than 0.1%. The main reason for this difference is that Automatic Gain Control units (AGC) used to stabilize RF voltage for the last two tanks are newer than that for other tanks, and are designed well in order to provide better stability. On the other hand, phases are nearly monotonically increasing or decreasing, which is often observed at RILAC. The low-level circuits for phase stability (Automatic Phase Control units) are the same for all tanks. The corresponding beam phases monitored by

two phase probes (PP-e11, X51) located downstream of RILAC are shown in Fig. 2. A beam phase (arrival time) changes depending on deviations of RF voltage and phase. Therefore, if we assume deviation of RF is small enough, we can define the first order coefficient of beam phase against RF deviation. We determined the coefficients using following two different method.

(1) Manually change RF voltage and phase for each tank, and measure the beam phase. (parameter change test)
(2) Fitting beam phase data with RF voltage and phase deviation.

For the case of (1), we changed RF voltage by 0.09–0.3% and phase 0.21–0.53°. For (2), the function used for fitting is

$$\phi^{\text{beam}} = \sum_{i=1}^{6} (a_i V_i^{\text{RF}} + b_i \phi_i^{\text{RF}}) + c$$

where ϕ_{beam} is the beam phase, V_i^{RF} and ϕ_i^{RF} are deviation of RF voltage and phase, respectively, and a_i, b_i, c are parameters. For comparison, data for fitting is separated into two: (2-a) initial 5.7 h, (2-b) last 6.5 h. In the fitting, a standard deviation of beam phase was assumed to be 0.015 ns taking noise level of PP into account. The fitting results of beam phase are shown in Fig. 2 as well as the values calculated by putting the parameters obtained in parameter change test into the fitting function. The results of fitting reproduce PP-data reasonably. Although an agreement with parameter change test is poor, fine structure is well reproduced. These results indicates that the fine structure of beam phase is actually caused by RF deviation. Fig. 3 compares the parameters obtained by parameter change test and by fitting. For the voltages of the last two tanks, parameters are significantly different between two methods. It seems that the fitting method can not determine these parameters because the RF voltages are nearly constant or not linear independent. Other than the last two tanks, the largest coefficient is that in the voltage of tank #2 (~ 3 [ns/%]). An improvement of a stability of beam phase was expected if AGC of tank #2 is upgraded to the same as that for the previous two tanks. Therefore, an upgrade of AGC was performed in September. A control system was also modified so that RF voltages for the first four tanks can be controlled in higher precision: from 1/3000 to 1/6000 for #1, #3 and #4, and #2 to 1/60000, the same as used in the previous two tanks. Fig. 4 shows the RF voltage and phase observed during
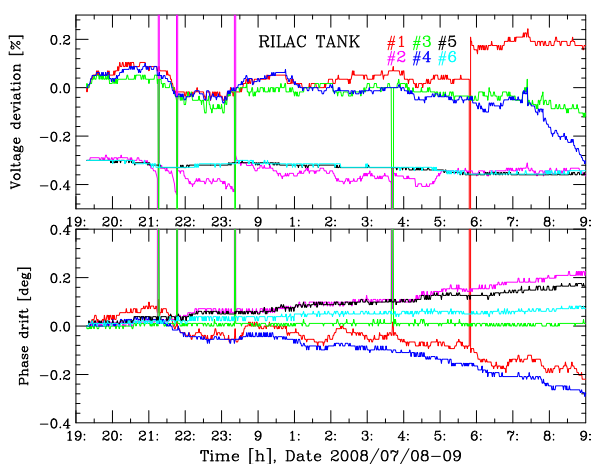
Fig. 1. RF voltage and phase of six tanks of RILAC. The voltage deviation (upper panel) for tank #2, #5 and #6 are shifted by −0.3% for visibility.

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Uranium acceleration in November. A time dependent fluctuation of voltage in tank #2 became similar to that in the last two tanks as expected. However, the voltages for these three tanks started to decrease similarly at around 0:00 on the 17th. As a result, stability is within 0.15%, and is worse compared with that in July (Fig. 1). The corresponding beam phase and parameter fitting results are shown in Fig. 5 and 3, respectively. PP-data during beam test (13:15 – 13:45) were eliminated from fitting. From the fitting results, a fluctuation of beam phase from 8:00 to 18:00 seems to be mainly due to the RF voltage deviation of #3. RF pickup voltage and phase are summarized in Tables 1 and 2. Further analysis is still in progress.
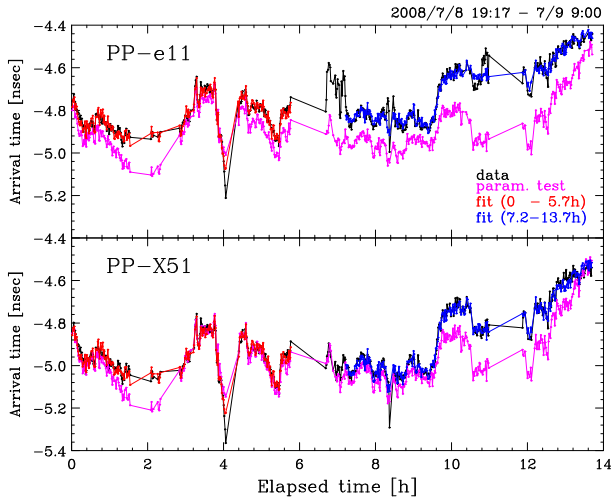
Fig. 2. Beam phase measured by two phase probes (PP-e11, X51) located downstream of RILAC. The data is compared with fitting results.
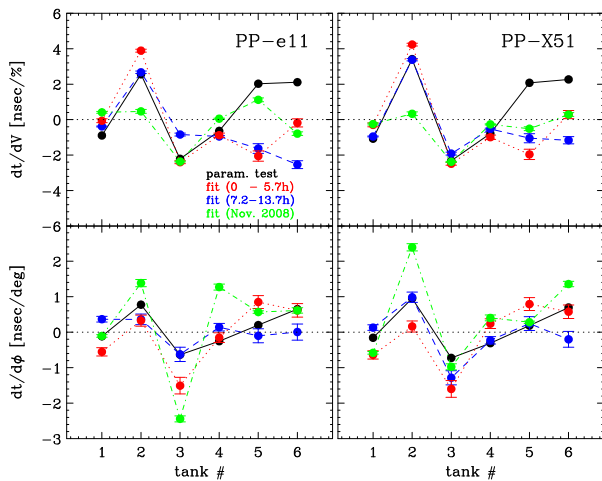
Fig. 3. Comparison of parameters obtained by parameter change test and fitting. Parameters a_i and b_i are shown in upper and lower panels, respectively.
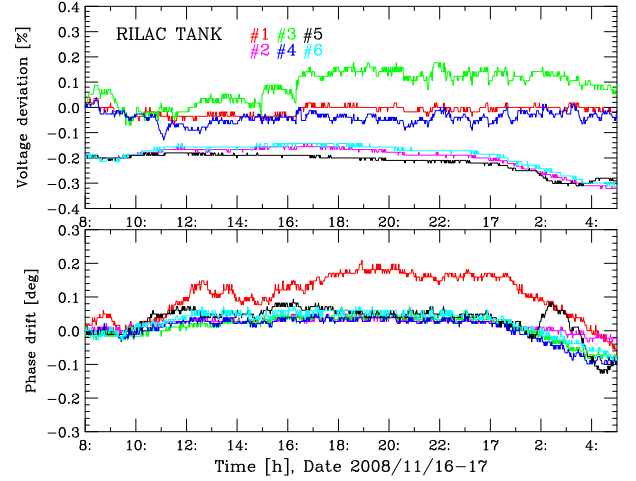
Fig. 4. RF voltage and phase of six tanks of RILAC. The voltage deviation for tanks #2, #5 and #6 are shifted by -0.2% for visibility.
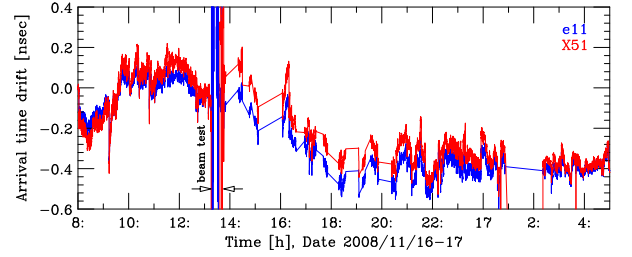
Fig. 5. Beam phase measured on 2008/11/16–17.

Table 1. RF pickup voltage and phase measured by LIA on 2008/07/08 19:17.

Tank #	1	2	3	4	5	6
Voltage [mV]	19.28	31.08	19.32	26.72	33.73	23.60
Phase [deg]	−81.72	−85.61	−80.00	−82.28	−71.16	−68.67
Phase(shifted)	0	−3.89	1.72	−0.56	10.56	13.05

Table 2. RF pickup voltage and phase measured by LIA on 2008/11/16 8:00.

Tank #	1	2	3	4	5	6
Voltage [mV]	18.99	30.47	19.00	25.84	33.29	23.47
Phase [deg]	−22.13	−30.36	−25.11	−28.16	−24.21	−20.66
Phase(shifted)	0	−8.23	−2.98	−6.03	−2.08	1.47

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- 123 -

Open-stub filter for fRC main amplifier

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The fixed-frequency ring cyclotron (fRC) in the RI-beam factory[1] has two accelerating resonators operated at 54.75 MHz.[2] Each resonator is fed by an rf amplifier based on a tetrode RS2058CJ with a grounded-grid configuration, and a maximum output power of 100 kW in the cw mode. The resonator and amplifier are connected by a 5 m coaxial waveguide (WX-120D). The typical input power for the acceleration of a uranium beam is 70 kW at a gap voltage of 450 kV.

There was a problem in these rf systems because the seventh harmonic component (383.25 MHz) became prominent in the resonators, as shown in Fig. 1, when the input power exceeded 40 kW. Apparently the harmonic component, transmitted from the amplifier, causes resonance of one of the resonant modes in the resonator coupled to the beam chambers. There are so many resonant modes in the frequency region above 350 MHz. In principle, the higher harmonic component should be as small as possible because the pickup signal from the resonator is rectified and used as input to the feedback loop of the amplitude.

Fig. 2. Cross sectional view of the open-stub filter.
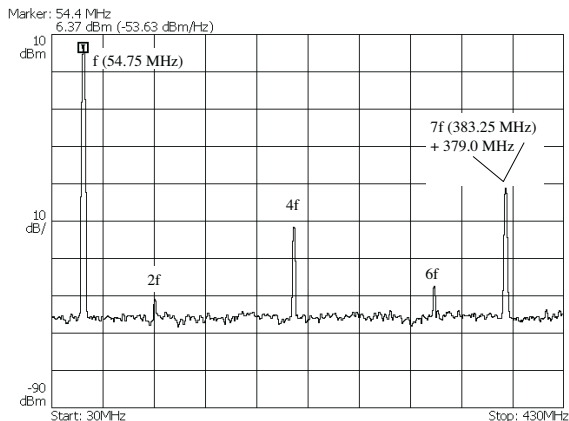
Fig. 1. Measured power spectrum of pickup signal of the accelerating resonator before installing the filter. Gap voltage was 440 kV. Although not shown clearly, the peak around the seventh harmonic component consists of two different components: 383.25 MHz and 379.0 MHz. The latter indicates self oscillations of the amplifier.

We first tried to suppress the harmonic component of the output power by re-adjusting the circuit parameters of the amplifier, but the improvement was quite limited. On the other hand, it seemed impossible to find an effective way to move the resonant modes far from the seventh harmonic frequency. Therefore, we decided to insert a notch filter in each waveguide, as illustrated below.

A schematic diagram of the filter is shown in Fig. 2, with an open stub added to a coaxial waveguide. The length of the open-stub is chosen to be approximately equal to the quarter wavelength at 383.25 MHz so that the transmission through the coaxial line is zero at this frequency. Since the length of the stub is much smaller than the wavelength at 54.75 MHz, insertion loss at the fundamental frequency is very small.

The size of the transmission ports of the filter is based on WX-120D. In order to adjust the notch center precisely, a moving plate was added to the open end of the stub. The length of the stub and the stroke of the plate were optimized by using the computer program Microwave Studio.[3] The thickness and position of the Teflon insulators were carefully taken into account in the calculation. All the components except for the inner conductor of the stub are made of copper, and the inner conductor is made of brass plated with copper.

The measured scattering parameter $|S_{21}|$ of the filter is shown in Fig. 3. Transmission at 383.25 MHz can be completely suppressed by adjusting the position of the end plate. Insertion loss at the fundamental frequency is very small, as expected. The filter was inserted into the waveguide close to the output port of the amplifier, as shown in Fig. 4.

The measured power spectrum of the pickup signal after installing the filter is shown in Fig. 5. It is clear that the higher order components are significantly reduced.

The filters worked stably during the uranium acceleration performed in this year.
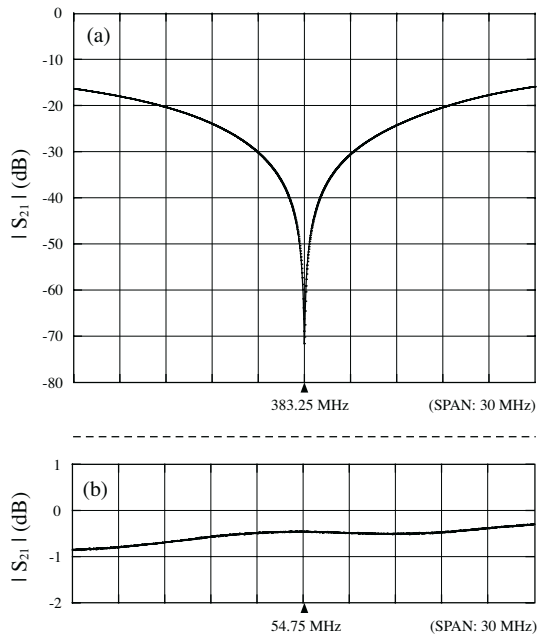
Fig. 3. Measured $|S_{21}|$ of filter in the frequency region around the seventh order component (a) and around the fundamental component (b).

Fig. 5. Measured power spectrum of pickup signal of the accelerating resonator after installing the filter. Gap voltage was 440 kV. The resultant peak corresponds to a frequency of 379.0 MHz. The seventh harmonic component (383.25 MHz) disappeared completely.

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Fig. 4. Photograph of filter installed in the amplifier.

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High-power test of four-rod cw RFQ for new injector to RI-beam factory

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As reported in the last volume,[1] an RFQ system[2] consisting of a resonator, rf power amplifier system, and water-cooling system, has been brought to RIKEN to be recycled as part of the new injector[3] for the RI-beam factory. High power tests of the resonator were carried out in 2008 as described below.

In February 2008, the water-cooling system was reassembled and new pipes were installed to supply de-ionized water for the resonator and the amplifier. The vacuum level in the resonator did not deteriorate in the presence of cooling water.

The rf amplifier mainly consists of two stages as shown in Fig. 1: the 5 kW driver stage based on a tetrode RS3021CJ, and the 50 kW final stage based on a tetrode RS2058CJ with a grounded grid configuration. A 500 W solid state amplifier is included in the driver stage. The amplifier was reassembled in the following way. First, in September 2008, the driver stage was brought to a factory and tuned to provide the designed power. At the same time, the program for the control unit was re-installed. Second, the final stage was reassembled at RIKEN and all the units including the DC power supply were connected with cables. Finally, the amplifier system was tested with a dummy load. We encountered no significant problems.

High power testing of the resonator started in December at 33.8MHz. So far, about 11 kW of power has been fed into the resonator in the cw mode. The estimated inter-vane voltage is 40 kV, which is sufficient for the acceleration of the designed ions with M/q=6.8 in the new injector. The vacuum stays at of 1×10^{-4} Pa during operation, and there seems to be no problem of heating. However, the vacuum pressure is insufficient for beam acceleration. In order to improve the vacuum pressure, two turbomolecular pumps of the RFQ will be replaced with cryogenic pumps.

The resonant frequency of the RFQ should be changed to 36.5 MHz when it is used in the new injector. We are planning to put block tuners in the resonator in this fiscal year. The calculation of the eigenmode has just started.

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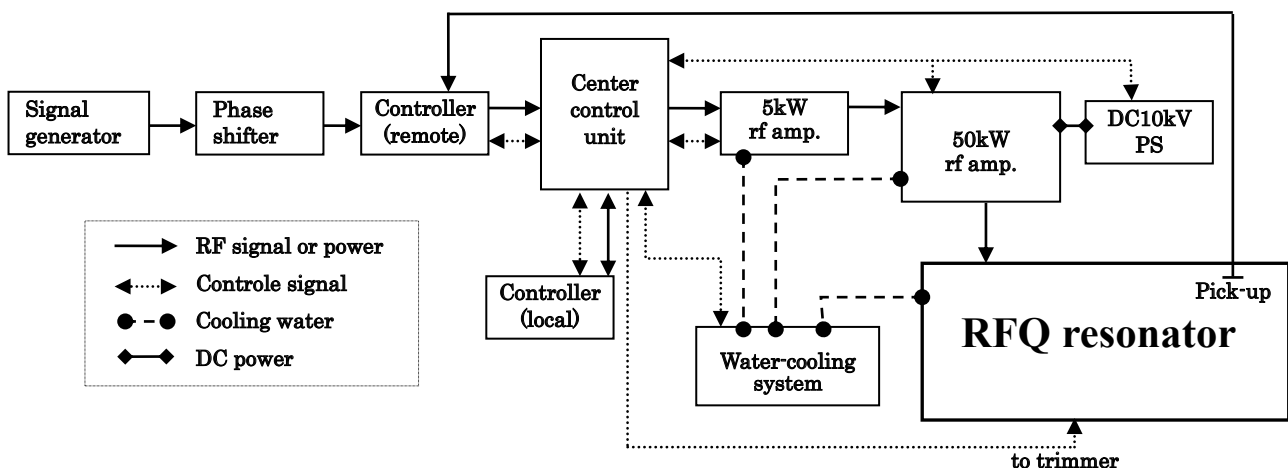
Fig. 1. Schematic block diagram of the RFQ system

Design of a water-cooling device for the rf shield of an SRC rf resonator

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It was required to design a device to prevent a cryogenic vacuum pump (the "cryopump") from being heated by thermal radiation from the rf shield of an SRC rf resonator.[1] The rf shield faces the cryopump, and its temperature reached a maximum of about 180 °C due to wall loss during operation of the rf resonator at the maximum voltage of 600 kV. Although installation of a cooling baffle was considered between the rf shield and cryopump for thermal shield, direct cooling of the rf shield was selected for reasons of gas flow conduction, on the condition that the device was attached to the rf shield without welding or brazing.

The water-cooling device mainly consists of an insert flange and a water-cooling pipe as shown in Fig. 1. The insert flange is made of stainless steel, and mounted between the cryopump and the port flange. The water-cooling pipe is a single seamless pipe made of oxygen free copper (OFC), worked by bending. Inner diameter and length of the pipe are 5 mm and about 3.8 m, respectively. Clamps made of OFC are brazed to the straight portion of pipe at intervals of 10 mm to provide flexibility so that the water-cooling pipe can be easily attached to the rf shield. The rf shield is pressed tightly between the clamps and equalizing plates with sixty-two M5 screws to ensure good thermal contact (See detail "A" of Fig. 1). Total length of the clamps are 2.3 m, and total contact area with the rf shield is 0.021 m².

The two ends of the water-cooling pipe are pulled out from the vacuum side into the atmosphere through two holes in the insert flange. Vacuum tightness is maintained by the shaft seal method using an O-ring in a groove with triangular cross section (See detail "B" of Fig. 1).

Wall loss of the rf shield is estimated to be roughly 2 kW. Under the assumption that all of this heat is removed by water flowing in the water-cooling pipe, various parameters were calculated so that the pipe flow velocity of water, pressure drop, and temperature increase were below 4 m/s, 0.15 MPa, and 10 °C, respectively. Table 1 shows the typical design parameters of the water-cooling pipe.

In heat transfer between the rf shield and water-cooling pipe, the temperature difference is caused by convective heat transfer at the inner wall of pipe, thermal conduction in the clamps, and thermal contact between the rf shield and clamps. Each temperature difference is approximately estimated assuming that the amount of heat transferred per unit time is 2 kW, and the water inlet temperature is 20 °C.

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Table 1. Typical design parameters of water-cooling pipe for heat input of 2 kW. λ is calculated using Blasius equation.

Volume flow rate of water (L/min)	4.0
Pipe flow velocity of water (m/s)	3.4
Reynolds number R_e	18900
Coefficient of pipe friction λ	0.027
Pressure drop (MPa)	0.13
Temperature rise of water (°C)	7.2

The heat transfer coefficient is calculated to be 15 kW/m²°C for the design volume flow rate of 4.0 L/min using the Dittus-Boelter equation. Using this value, the logarithmic mean temperature difference, and the pipe wall temperature are estimated to be 7.3 °C and 31.5 °C, respectively.

The temperature difference in the clamps is calculated to be 3.6 °C. As a result the contact surface temperature of clamps with the rf shield is 35.0 °C.

The thermal contact resistance can be estimated using the Tachibana[2] and Sanokawa[3] equations. According to those equations, the resistance is proportional to solid hardness, inversely proportional to thermal conductivity and contact pressure, and slightly affected by solid surface roughness if both solids are made of the same material. For a hardness of 112 (HB) and a contact pressure of 7.1 MPa, the thermal contact resistance is calculated to be about 6.8×10^{-5} (m²°C/W). By using this result, the temperature difference is calculated to be 6.5 °C. Consequently the temperature around the top of rf shield is expected to be about 42 °C.

According to the manufacturer of the cryopump an allowable thermal load for a refrigerator of cryopump can be substituted for an allowable temperature of a surface with an emissivity facing the cryopump, and in the case of a surface with emissivity of 0.6 a permissible temperature of surface is below 58 °C .[4] Assuming that emissivity of the rf shield is at the same level as copper oxide, which is commonly considered to be below ~0.6, the temperature of the rf shield is expected to be appreciably lower than that permissible.

Although the cryopump has a pumping speed of 10 m³/s for nitrogen gas, the effective pumping speed at the bottom of the rf shield should be considered from a practical standpoint. When connecting conducting elements (e.g. tubes, baffles, etc.) for molecular flow in series when the cross-sectional areas are different, it is convenient to use a transmission probability (a so-called Clausing's factor), and the relation is expressed
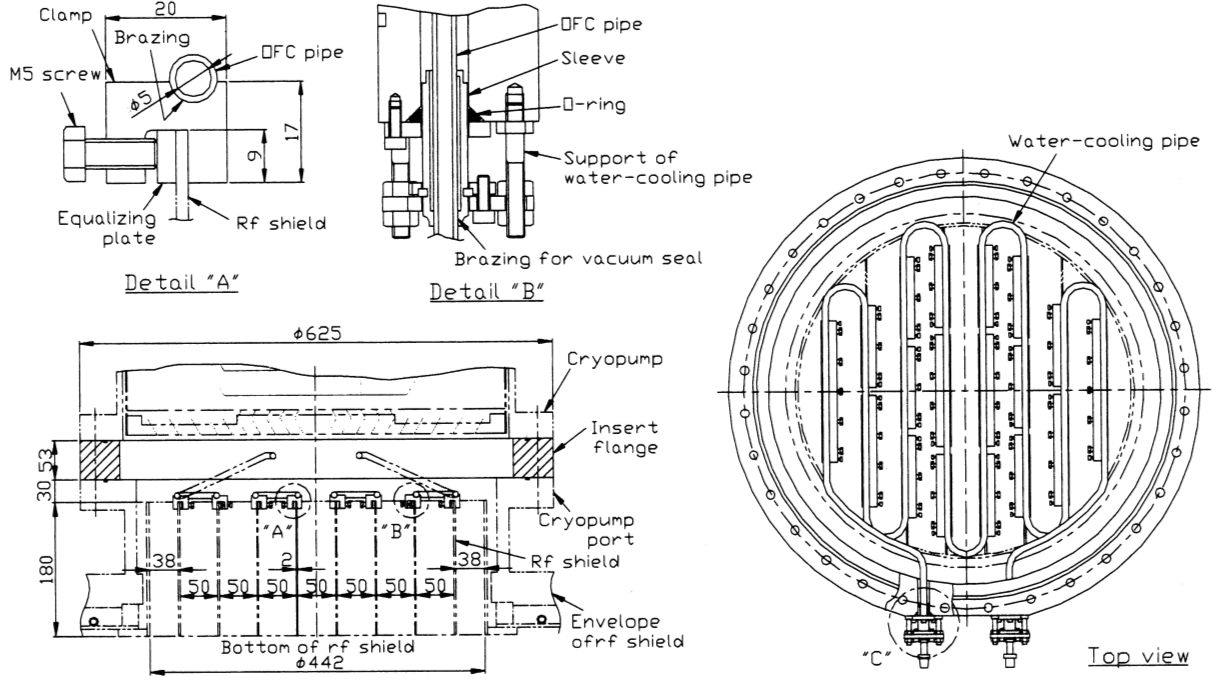
Fig. 1. Structural drawing of the water-cooling device.

by Eq. (1)[5]

$$\frac{1}{A_1 W_{1n}} = \frac{1}{A_1} + \sum_{i=1}^{n} \frac{1}{A_i}(\frac{1}{W_i} - 1)$$
$$+ \sum_{i=1}^{n-1} \frac{1}{A_i}(\frac{A_i}{A_{i+1}} - 1)\, \delta_{i,i+1}\,,$$
$$\delta_{i,i+1} = 1 \quad \text{for} \ A_{i+1} < A_i,$$
$$\delta_{i,i+1} = 0 \quad \text{for} \ A_{i+1} \geq A_i, \tag{1}$$

where n is the number of of elements, W_{1n} is the total transmission probability passing through from the entrance of the first element to the exit of the nth element, and W_i and A_i are the transmission probabilities and cross-sectional areas of the individual elements, respectively. A pumping probability which denotes the ratio of the pumping speed to the conductance of the pump inlet has the same meaning as a transmission probability. Therefore, when a vacuum pump is connected to a chamber by conducting elements in series, the effective pumping probability is also derived from Eq. (1) by adding the vacuum pump as the last element. Table 2 shows the transmission probability and cross-sectional area of individual elements and the effective pumping probability without and with the water-cooling device. The effective pumping speed is obtained as the product of the conductance and effective pumping probability at the bottom of the rf shield, and the conductance for nitrogen gas at 20 °C is determined by multiplying 118 $(\mathrm{m^3/s\,m^2})$ by the cross-sectional area of the rf shield. The effective pumping speed with and without the water-cooling de-

vice for nitrogen gas at 20 °C are eventually calculated to be 4.6 and 4.1 $\mathrm{m^3/s}$, respectively.

Two water-cooling devices were manufactured and installed at the number 2 and 4 rf resonators in 2008, and the SRC vacuum is performing well.

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Table 2. Transmission probability and cross-sectional area of individual elements, and effective pumping probability with and without the water-cooling device. Transmission probability of the water-cooling pipe was calculated as a rough estimate due to the labour involved.

Element	Transmission probability	Cross-sectional area $(\mathrm{m^2})$
Rf shield	0.358	0.153
Water-cooling pipe	0.703	0.177
Opening of cryopump port	0.941	0.177
Insert flange	0.907	0.212
Cryopump	0.415	0.204
Effective pumping probability		
without device	0.256	
with device	0.229	

The heating effect of cryogenic vacuum pump of SRC rf resonator

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The SRC has four rf resonators (RES1, RES2, RES3, and RES4). Each rf resonator is evacuated by three cryopumps (CP1, CP2, and CP3) whose nominal diameter is 500 mm as shown in Fig. 1. A vacuum pressure inside an rf resonator is kept as low as 10^{-6} Pa when an rf voltage of the rf resonator is less than 500 kV. However, a vacuum pressure inside RES4 became high above a permissible level after its rf voltage was raised up to a design value of 600 kV. The variation of temperature inside every cryopumps and vacuum pressure of RES4 is shown in Fig. 2. A temperature of 80K baffle (T_1), which was considered to be approximately 50 K higher than that of 1st stage of refrigerator, was also measured as well as that of 2nd stage (T_2). The T_1 and T_2 of CP1 increased with time, and reached above 40 K and 200 K at t = 4 hours, respectively. On the other hand, the T_1 of CP2 and CP3 changed little with increase in time. The vacuum pressure increased steeply with time just after t = 0, and at t = 2 hour fell rapidly to around 1×10^{-5} Pa. This drastic increase in pressure is considered to be caused by a large amount of hydrogen gas desorbed from an adsorption panel of CP1 due to increasing T_2 above ~20 K.

Wall loss has a peak value at the centre of rf resonator, and decreases with a distance from it. Since CP1 faces to the centre of rf resonator, input power to rf shield at CP1 port is larger than that to others. Therefore, this rf shield may be heated too much if it is not water-cooled sufficiently.

A check inside RES4 was carried out. As a result about half of screws, which fixed rf shield to copper plate (See Fig. 1(b)), turned out to be loose. After tightening these screws by a roughly 1/4 turn (re-tightening), T_1 and T_2 of CP1 were measured. The measured result is shown in Fig. 3. Although both T_1 and T_2 after re-tightening were lower than those before re-tightening, the T_1 did not decrease below 130k equivalent to a permissible value of 80 K for 1st stage.

In order to decrease T_1 bellow 130 K, it was concluded that an rf shield at CP1 had to be cooled to prevent CP1 from being heated by thermal radiation from it. A water-cooling device for an rf shield was designed.[1] The device is chiefly composed of an insert flange of stainless steel and a cooling pipe of oxygen free copper which is built in the insert flange and clamps end face of the rf shield (See Fig. 4). Only two pieces of device were manufactured for RES2 and RES4, and installed at each CP1 port. Figure 5 shows T_1, T_2 and vacuum pressure for RES2 and RES4 after installing a water-cooling device. The T_1s were kept below a permissible temperature of 130 K, and the T_2s were

kept as low as 15 K. The vacuum pressures were kept approximately between 1 to 2×10^{-5} Pa, although small peaks were observed within t = 2 hours. The devices for RES1 and RES3 are now in manufacturing, and will be installed in February 2009.

(a)

(b)
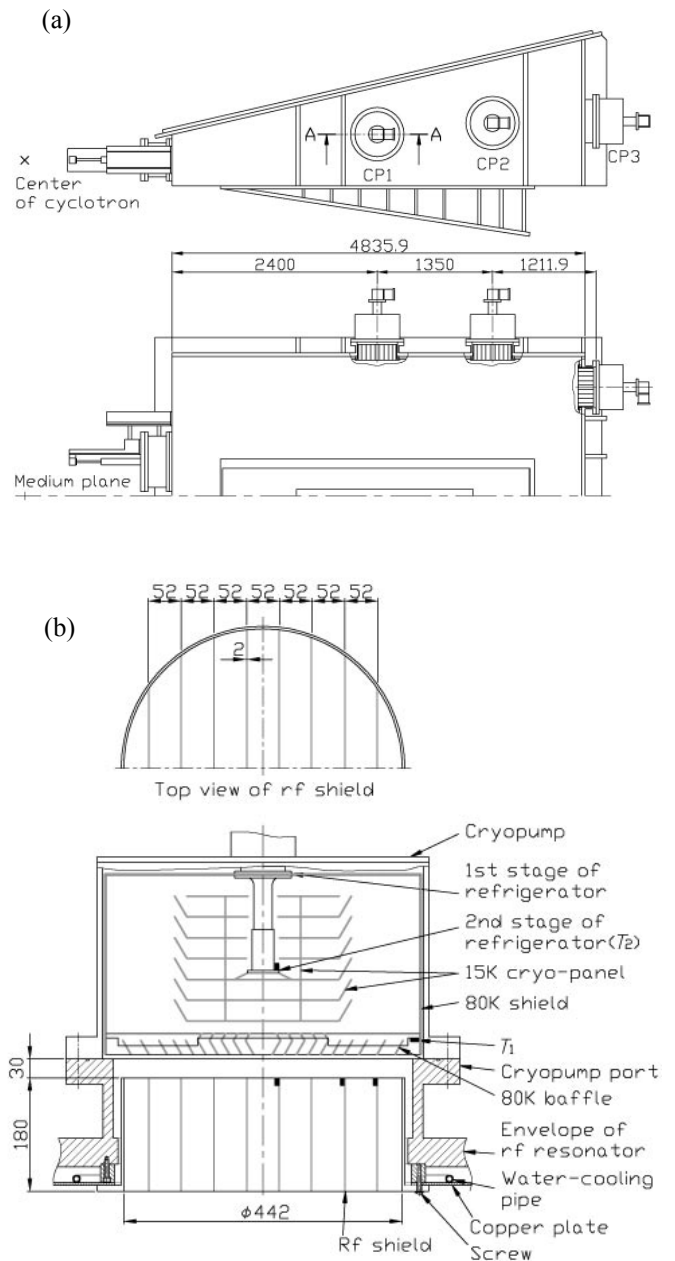
Fig. 1. (a) Layout of cryopumps installed for an rf resonator. (b) Cross-sectional view of A-A in (a) and top view of rf shield.

* SHI Accelerator Service, Ltd.
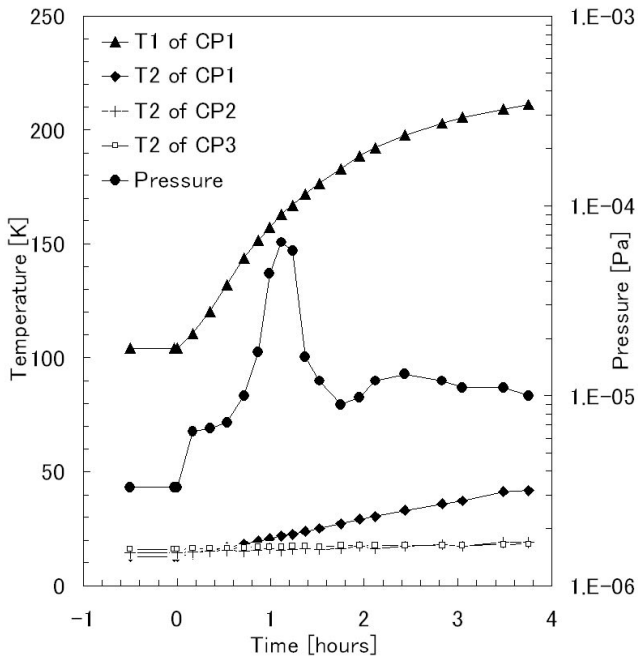
Fig. 2. The variation of temperature inside cryopumps, and vacuum pressure for RES4 after its rf voltage was set to 600kV at t=0 in.

Fig. 4. Photograph of water-cooling device mounted at cryopump port flange.

Fig. 3. The variation of temperature inside cryopumps, and vacuum pressure for RES4 after its rf voltage was set to 600kV at t=0 after re-tightening.
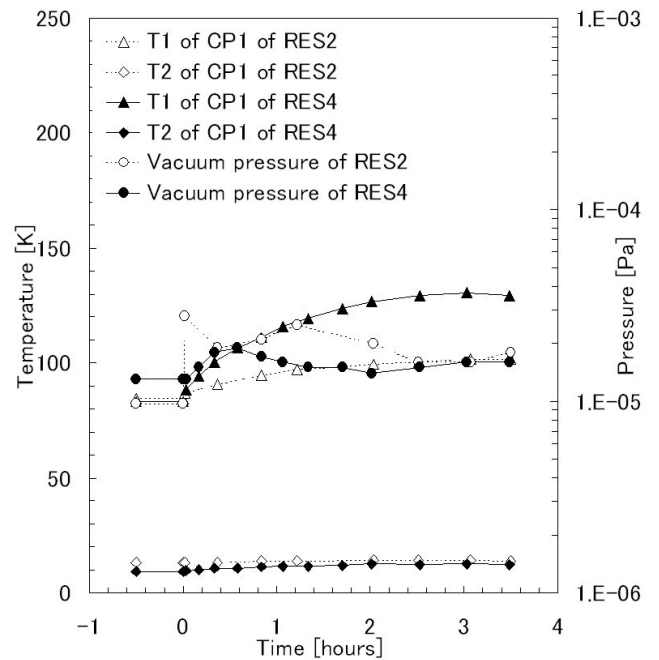
Fig. 5. The variation of temperature inside cryopumps, and vacuum pressure for RES2 and RES4 after each rf voltage was set to 600kV at t = 0 after installing a water-cooling device. The solid lines represent the temperatures and pressure for RES4, and the dashed lines denote those for RES2.

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The effect of vacuum pressure on transmission efficiency of RILAC

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It is strongly required to improve the transmission efficiency of the RIKEN heavy-ion linac (RILAC) in order to obtain a higher beam intensity of uranium beam in the RI beam factory (RIBF).[1] The transmission efficiency of $^{35+}$U beam in RILAC was as low as 31% during the commissioning in early 2008, which is appreciably lower than typical transmissions, e.g. ~41% for $^{+13}$Fe, and ~53% for $^{+16}$Zn.

In the case of the acceleration and transport of a high-charge state heavy ion such as $^{35+}$U in RILAC, the loss via the charge-exchange processes of the beam with residual gas in vacuum chambers may decrease the transmission efficiency. In fact, vacuum pressures of RILAC had been in the range of 10^{-5} Pa. The vacuum required for the low energy $^{35+}$U beam transport was estimated to be as low as 10^{-6} Pa to keep the beam loss negligible. We investigated the effect of the vacuum pressure along the RILAC beam line on the overall transmission efficiency.

Figure 1 shows a layout of the RILAC. All the vacuum pumping system are shown in the figure. The whole beam lines are divided into fourteen sections; RFQ, rebuncher, six RILAC cavities and the beam lines between them. Each section is equipped with one or two vacuum pumping systems via an individual vacuum valve (VH). We measured the change in the overall transmission from RFQ to the CAVITY#6, when the vacuum pressure in section x was intentionally increased by closing the corresponding VH_x without changing the vacuum in neighboring sections.

The overall transmission efficiency of the RILAC that is defined as a ratio of the beam intensity at the location of e11 to that at the location of R1 is denoted by η_o which is obtained after sufficient beam tuning. Suppose that the initial transmission η_o is degraded to η_x as the vacuum pressure in section x is raised from the initial value po_x to pm_x after VH_x is closed,

Since η_x / η_o denotes change in transmission of the vacuum section x, a beam loss (λm_x), which occurred additionally in the section is 1- η_x / η_o. λm_x is considered to be approximately linear with respect to sufficiently small defferences in the vacuum pressure, Δpm_x, ($= pm_x - po_x$) assuming that both cross section and path length are constant. Therefore, an intrinsic beam loss (λ_x) in the section x is calculated by $\lambda_x = \lambda m_x \times (po_x / \Delta pm_x)$.

Thus the estimated values from the measurements of λ_x

at each section are plotted in Fig. 2. The beam loss in the upstream of RILAC was larger than that in the downstream expectedly. This result suggests that the vacuum effect on transmission efficiency is larger in the upstream of RILAC and that the improvement of the vacuum in the upstream is therefore more important. Although the λ_x in the section VAC12 looks large in Fig. 2, it was caused by a temporary increase in vacuum pressure during measurement and was certified to be normally as low as that in other sections in the downstream later.

Based on these results, the pumping systems for the three upstream sections, RFQ, 014, and CAVITY#1 were reinforced in the summer of 2008 as follows: one of the 1500 L/s TP's was replaced by a 2400 L/s CP in the RFQ, one new 220 L/s TP was added at the 014, and 2400 L/s TP was replaced to 13000 L/s CP in CAVITY#1. As for the rebuncher (REB), its vacuum system could not be improved under present circumstances. The estimation of effective pumping speeds for these three sections before and after the changes are summarized in Table 1. The changes in the vacuum pressures of the three sections are shown in Figure 3, and have improved corresponding to the increase in pumping speeds.

We received a transmission of ~40% during beam testing autumn 2008. This value for the transmission was improved by 10% from previous ones which can be explained by the measurement results in table 2. This improvement in transmission efficiency is thought to be mainly attributed to the reduction in the vacuum effect.

Section	Total pumping speed(L/s)		Improved ratio
	Before improvement	After improvement	
RFQ	1114	1672	1.5
014	216	376	1.7
CAVITY#1	4426	10585	2.4

Table 1. Comparison of total effective pumping speeds of CAVITY#1,RFQ, 014 and CAVITY#1 before and after the improvement of vacuum pumping system. Improved ratio represents the ratio of total effective pumping speed after the improvement to that which previously occurred.

* SHI Accelerator Service, Ltd.
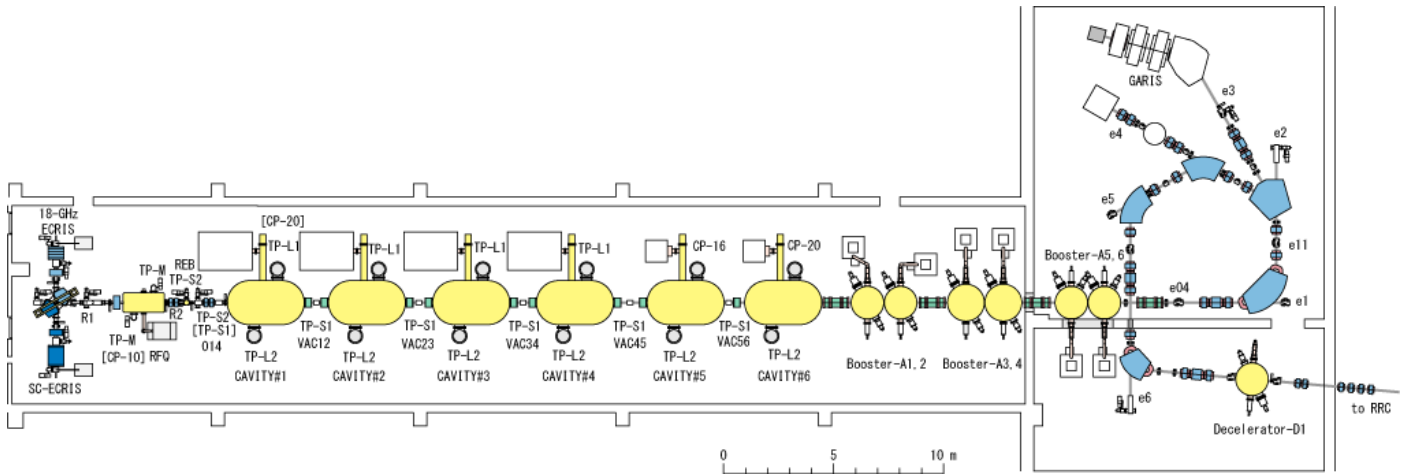
Fig. 1, Layout of the RILAC. TP denotes a turbomolecular pump, and the nominal pumping speeds of TP-, TP-L2, TP-M, TP- L1S1, and TP-S2 are 5000, 2400, 1500, 350, and 220 L/s respectively. CP- represents a cryopump, and the nominal pumping speeds of CP-20, CP-16, and CP-10 are 13000, 5000, and 2400 L/s respectively. Names in parentheses indicate those of the vacuum pumps replaced and name in brackets shows that of the vacuum pumps added in the improvement of the vacuum pumping system. The transmission efficiency of the RILAC is defined as the ratio of beam currents through e11 to that through R1.

	P0x(x10-6Pa)	Pmx(x10-6Pa)	λx(%)	Dλx(%)
RFQ	1.1E-05	4.7E-06	8.8	4.9
ReB	4.1E-05	2.9E-05	6.8	2.0
Cavity#1	7.2E-05	2.7E-05	7.6	4.8
Total				11.7

Table 2. The reduction of beam losses expected from improvement of vacuums in the three sections; RFQ, ReB, and Cavity#1. The result shows the transmission can be improved by a total of 12%.
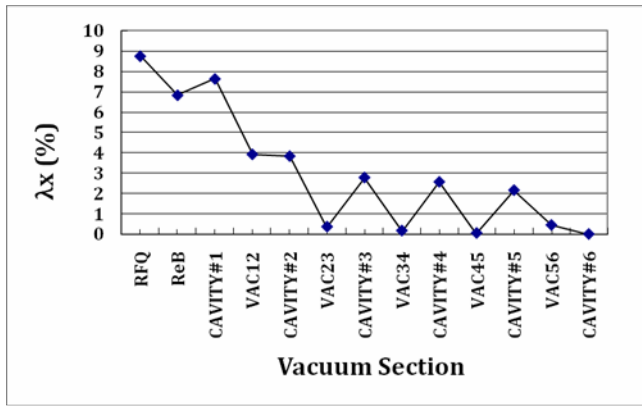
Fig. 2, Plot of intrinsic beam loss at each section

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1) N. Nobuhisa et al.: RIKEN Accel. Prog. Rep. **41**, 85 (2008).
2) Y. Sato: private correspondence
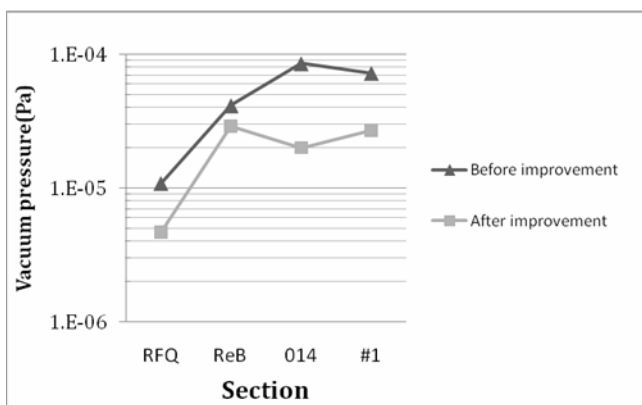
Fig. 3, Comparison of vacuum pressures of RFQ, REB, 014, and CAVITY#1 before and after the improvement of the vacuum pumping system when all GVs were open.

Development of polymer-coated carbon stripper foils

H. Hasebe, H. Okuno, H. Kuboki, N. Fukunishi, O. Kamigaito A. Goto, M. Kase, and Y. Yano

Carbon foils (C-foils) are extensively used as charge strippers for heavy-ion beams at the RIKEN RI beam factory. As thicker C-foils became necessary, we started to develop polymer-coated carbon foils (PCC-foils)[1] in 2005.

A beam test on the lifetime of C-foil with a fixed holder, with a racetrack-shaped hole of 14 mm x 23 mm, was performed in April 2008. The foil consisted of 5 poly-monochloro-para-xylylene (Parylene) layers and 5 carbon layers. Multi-layer PCC-foils were irradiated with a 11 MeV/u ^{238}U^{35+} beam at an intensity of 0.5 eμA that was delivered from the RIKEN ring cyclotron (RRC). The beam spot size was approximately 5 mm in diameter. The lifetime was determined by monitoring both the beam intensity of the stripped ions and the image of the C-foil on a TV display. Figure 1 shows photographs of two examples of multi-layer PCC-foils of 300 μg/cm^2 in carbon thickness after irradiation. Although the both foils were made in the same way, their lifetimes were substantially different; the foil in Fig. 1 (a) ruptured in a very short time and that in Fig. 1 (b) did not deteriorate even after 15 hours. Multi-layer PCC-foils are easily deformed by the heat due to beam irradiation because of the characteristics of Parylene.

Since the lifetime would become long if the Parylene was evaporated well or its polymer characteristics were lost, the final layer of the five Parylene layers was not deposited and the foils were put in an oven at 523 K (250 °C) for several hours before release off the glass substrate. PCC-foils made in this way stopped rupturing instantly, and all of them were usable for 6–24 hours in a beam study performed in July 2008. The beam condition in this beam study was the same as that of the previous test in April. These lifetimes are almost the same as those of C-foils (XCF-300) of the Arizona Carbon Foil Co. Inc.
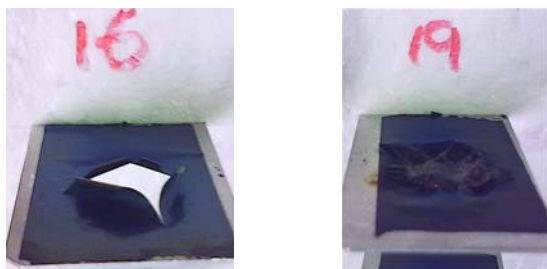
Fig. 1. Photographs of the 300 μg/cm²-thick multi-layer PCC-foils after irradiation with a ^{238}U^{35+} beam: (a) PCC-foil that ruptured in a short time and (b) PCC-foil that was still usable after more than 15 hours.
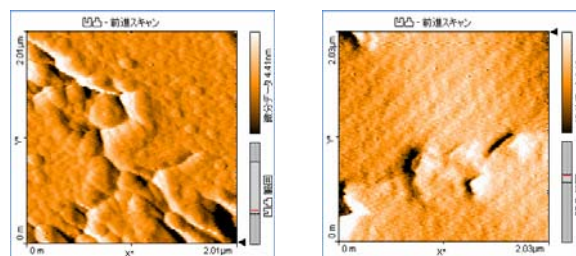
(a)   (b)

Fig. 2. AFM images of the surface of the substrate side of the 300 μg/cm^2-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.
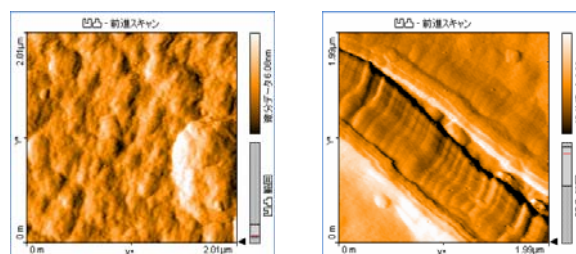
(a)   (b)

Fig. 3. AFM images of the surface of the evaporating source side of the 300 μg/cm^2-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

An Atomic Force Microscope (AFM)[2] was introduced to observe the surface of thin C-foils. Figures 2 and 3 show the observed surface images of the non-irradiated part and the irradiated part of the 300 μg/cm^2-thick PCC-foils, respectively. The imaged area size was 2 μm x 2 μm. The surface of the substrate side of the non-irradiated part, as shown in Fig. 2 (a), was observed to be flat with a small amount of rough area and to have crushed carbon mounds (200 – 300 nm in diameter). On the other hand, the surface of the evaporating source side, as shown in Fig. 3 (a), was observed to be quite rough and to have many carbon mounds attached. The surface of the PCC-foils after beam irradiation changed drastically. The surface of the substrate side of the irradiated part, as shown in Fig. 2 (b), was observed to have no carbon mounds but to be in a melted state. The surface of the evaporating source side, as shown in Fig. 3 (b), was also observed to have no carbon mounds but big cracks. The surface of the evaporating source side changed more drastically than that of the substrate side; this is the reason why we stopped depositing the final layer of the five Parylene layers.
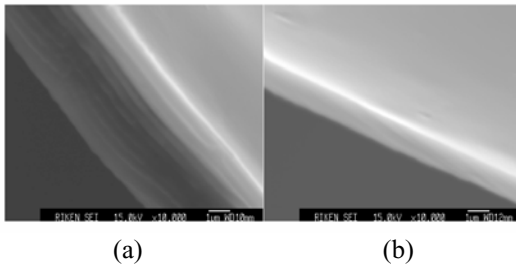
Fig. 4. SEM images of the cross section of the 500 $\mu g/cm^2$-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

A multi-layer PCC-foil of 500 $\mu g/cm^2$ in carbon thickness, which was used as a charge stripper in another beam study, was observed with an Scanning Electron Microscope (SEM)[3] and an Electron Probe Micro Analyzer (EPMA)[3] . The beam condition was the same as in the beam test on the lifetime of foils. Fig. 4 (a) and (b) show SEM images of the cross section of the PCC-foil at the non-irradiated part and irradiated part, respectively. The irradiated part was observed to be one layer with 1 μm in thickness due to evaporation of Parylene, while the non-irradiated part was observed to be 10 layers with 3 μm in total thickness. The reason for the drastic decrease in thickness is thought to be heat deformation by the beam. Fig. 5 (a) and (b) show results of qualitative analysis using the EPMA for the non-irradiated part and irradiated part, respectively. Peaks of Ar from the sputtering source and Cl from Parylene observed in the spectra for the non-irradiated part disappeared in that for the irradiated part.
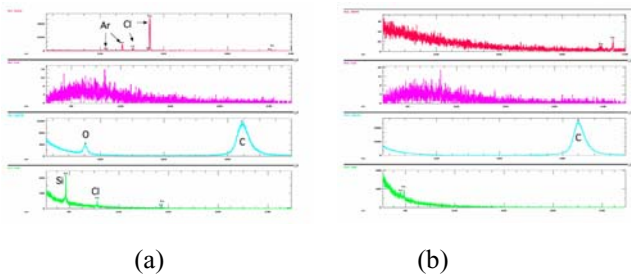
Fig. 5. Results of qualitative analysis using an EPMA for the 500 $\mu g/cm^2$-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

The lifetime of multi-layer PPC foils set in the rotating-cylinder stripper device[4] was measured in May 2008. The foils were made of 5 layers of carbon plus 5 layers of Parylene (the final layer of Parylene was still deposited), with carbon thickness of 300 $\mu g/cm^2$ and diameter of 10 cm. The foils were rotated with a speed of 100–300 rpm and the beam was again a 11 MeV/nucleon $^{238}U^{35+}$ beam with an intensity of 0.5 eμA. The measurement was performed for two foils: the first one was treated in the oven at 573 K (300 °C) for 2.5 hours before releasing it off the glass substrate and the second one was not treated. The result was that both foils ruptured in a time as short as 25 min. and 10 min, respectively. Figure 6 shows a photograph of the first foil after beam irradiation. A lot of holes were produced almost all along the beam-irradiated

ring area, and a big circular area inside the ring was torn off the foil when it was taken out from the device (see Fig. 7). The width of the beam-irradiated ring area was estimated to be approximately 5 mm, which corresponded to the beam spot size. A diamond-like C-foil manufactured by TRIUMF[5] also ruptured in the same way after approximately 9 hours irradiation. The lifetimes of C-foils for the rotating-cylinder stripper device were found to be worse than or equivalent to those for the fixed holder, contrary to the expectation that the former would provide tens of times better performance than the latter. The rapid change in temperature in the beam-irradiated area due to the slow rotation speed might cause such results.

Fig. 6. Photograph of the 300 $\mu g/cm^2$-thick multi-layer PCC-foil that was set in the rotating-cylinder stripper device and ruptured after 25-min beam irradiation. The ring area was discolored due to beam irradiation.
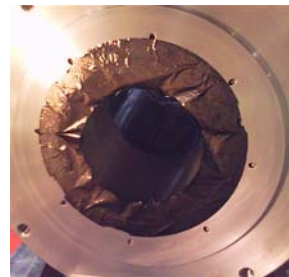
Fig.7. Same as Fig. 7 except that the foil was removed from the device. A big circular area inside the ring was torn off the foil.

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5) TRIUMF Carbon Foil Laboratory

Offline test of a gas charge stripper for uranium beams

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Charge strippers play an essential role in a heavy-ion accelerator complex, since a high-charge state enables an acceleration of heavy-ion beams up to a high energy with small accelerators. The ions at a higher velocity are charge-stripped to a higher charge state[1]. Therefore, the efficient acceleration of heavy-ion beams is realized by charge strippers placed between sequentially connected accelerators.

The RIKEN RI-beam factory (RIBF) is such a heavy-ion accelerator complex[2]. At the RIBF, two stripper sections are used to accelerate uranium ions up to 345 MeV/nucleon[3]. Figure 1 shows a schematic view of the RIBF. Heavy ions extracted from the
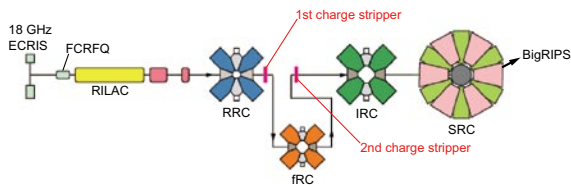
Fig. 1. Schematic view of the RIBF. The accelerators are shown with the ion source and the two charge strippers.

RIKEN 18 GHz ECR ions source[4] are accelerated successively by the RIKEN heavy-ion linac (RILAC), the RIKEN ring cyclotron (RRC), the fixed-frequency ring cyclotron (fRC)[5], the intermediate-stage ring cyclotron (IRC)[6], and the superconducting ring cyclotron (SRC)[7]. The two stripper sections are placed downstream of the first two cyclotrons, the RRC and the fRC. The beam energies incident on these two strippers are 11 and 51 MeV/nucleon, respectively. The first charge stripper strips uranium ions with a charge state of 35+ to 71+ which is the lowest charge state that enables uranium ions to be accelerated with the fRC. The second charge stripper strips U^{71+} ions to U^{86+} in order to accelerate uranium ions with the IRC. At present, carbon foils with a thickness of 300 $\mu g/cm^2$ and 13.9 mg/cm^2 are used as the first and second charge strippers, respectively. The irradiation conditions at the two stripper sections are summarized in Table 1. Especially, the first stripper has two serious problems : 1) The foils have short lifetime (at most 24 hours) caused by heat load and mechanical stress of the irradiation. 2) The energy spread of the beam after the first charge stripper is estimated to be 0.55% (4σ value)[8] , which is beyond the acceptance (0.2%) of the rebuncher[9] placed between the RRC and the fRC.

We focus on a gas charge stripper as a new can-

didate to overcome two problems mentioned above, since a gas charge stripper has a very uniform thickness and is tolerant of heat load. One weak point is that a charge state lower than 71+ may be obtained due to the *density-effect*[10]. In the case of gas strippers, the time between collisions is sufficient for excited projectiles to return to their ground states before entering into subsequent collisions. Since the cross section for ionization is larger when projectiles are in excited states than when projectiles are in the ground state, we may obtain charge states lower than that in the case of carbon foil strippers. A semi-empirical formula obtained by Sayer[11] predicts that the charge state we can obtain using a gas charge stripper would be 63+. However, the data used to derive the formula does not match our case. Perumal et al.[10] have also mentioned charge states of uranium ions stripped by gas charge strippers. The highest energy referred in Ref.[10] has been 3.5 MeV/nucleon. Therefore, no one actually knows the charge states of uranium ions obtained by gas charge strippers at $\sim$10 MeV/nucleon.

We have developed a gas charge stripper using the windowless type gas target system[12]. An overview of the gas charge stripper system for offline test is shown in Fig. 2. Figure 3 shows a schematic diagram together
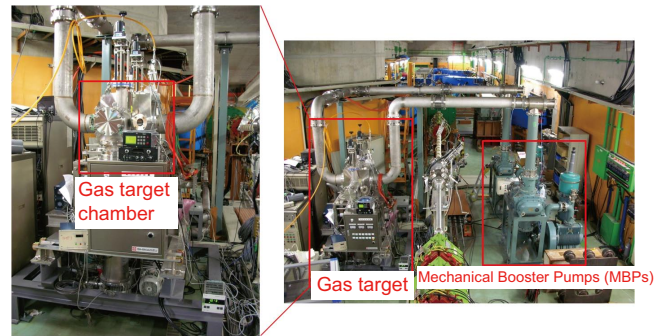
Fig. 2. Overview of the gas charge stripper system located at the D-room.

with its differential pumping system. The region in the target cell is defined as stage 1. The length of the target cell is 10 cm. The region outside of the target cell is defined as stage 2. Similarly, stage 3–5 denote the regions outside of stage 2–4, respectively. The pressure at each stage is indicated by P_1–P_5, respectively. Since the gas charge stripper is operated in a beamline, the pressure P_1 should be high and the pressure away from the target cell should fall as rapid as possible. We performed an offline test of the gas charge stripper with nitrogen gas injected into the target cell. The results

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Table 1. The irradiation conditions at the two stripper sections.

stripper	ion	energy (MeV/nucleon)	carbon thickness	beam intensity (pnA)	heat load (W)	spot diameter (mm)
1st	$^{238}U^{35+}$	11	300 (μg/cm^2)	14	0.50	5
2nd	$^{238}U^{71+}$	51	13.9 (mg/cm^2)	3.7	3.2	5

are shown in Fig. 4. The pressures P_2–P_5 are plotted as a function of P_1. We can obtain higher charge states
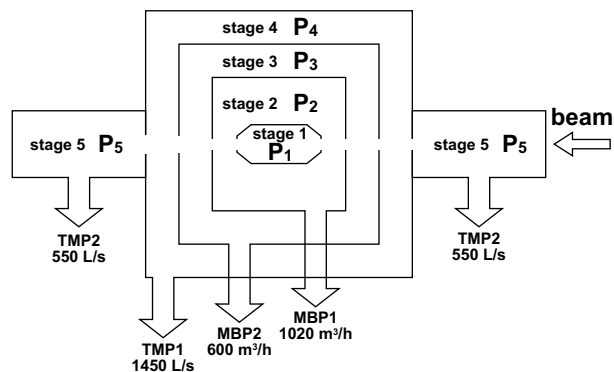
Fig. 3. Schematic diagram of the gas charge stripper with its differential pumping system[12]. The target cell (stage 1) is located at the center. The length of the target cell is 10 cm. Other stages are also shown with pumping speeds of the attached pumps. Four apertures before the beam entrance into the target cell are 6 mm in diameter. The exit of the target cell and the exit of the stage 2 have also 6 mm diameter apertures. The exit of the stage 3 and 4 have 8 mm and 10 mm diameter apertures, respectively.
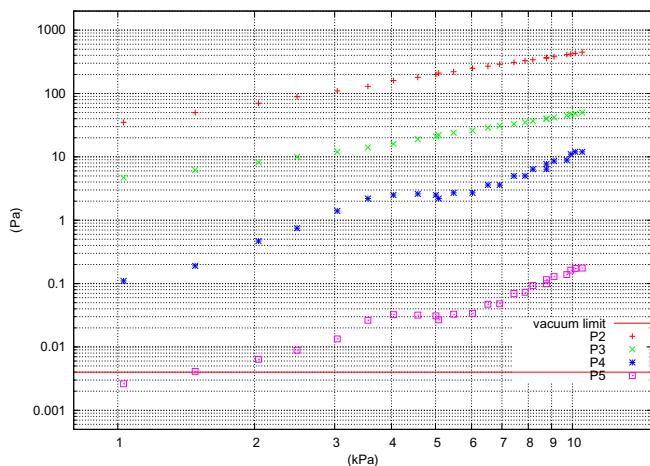
Fig. 4. The pressure at each stage is plotted as a function of P_1. Solid line shows the limit for an interlock (4×10^{-3} Pa).

with a thicker charge stripper. However, in the case of carbon foils, the averaged charge state achieves equi-

librium at a thickness of 500 μg/cm^2 [3]. With an assumption that the thickness for an equilibrium charge state using nitrogen gas is the same as that in the case of carbon foils, the thickness above 500 μg/cm^2 should be needed. The thickness estimated from the maximum pressure of 10.5 kPa was 1.18 mg/cm^2. However, a limitation of P_1 is practically determined by P_5. The pressure P_5 should be lower than 4×10^{-3} Pa which is the limit for an interlock. The results indicate that the pressure P_1 should be maintained lower than 1.4 kPa (157 μg/cm^2) to keep the pressure P_5 under the limit.

We are planning to obtain data of the charge distribution with uranium beams at 11 MeV/nucleon in March 2009. To control P_1 up to higher pressure, an additional stage (stage 6) and a couple of turbo molecular pumps will be introduced. A test with helium gas is also planned to investigate dependence on materials.

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Practical use of beam current monitor with HTS current sensor and HTS SQUID at RIBF

T. Watanabe, Y. Sasaki, M. Kase, N. Fukunishi and Y. Yano

A highly sensitive beam current monitor with an HTS (high-temperature superconducting) SQUID (superconducting quantum interference device) and an HTS current sensor, that is, an HTS SQUID monitor, has been developed for use with the RIBF (RI beam factory) at RIKEN[1–3]. Unlike other existing facilities, the HTS SQUID monitor allows us to measure the DC of high-energy heavy-ion beams nondestructively in real time, and the beam current extracted from the cyclotron can be recorded without interrupting the beam user's experiments. Both the HTS magnetic shield and the HTS current sensor were dip-coated to form a Bi_2-Sr_2-Ca_2-Cu_3-O_x (Bi-2223) layer on 99.9% MgO ceramic substrates. In work conducted presently, all the fabricated HTS devices are cooled by a low-vibration pulse-tube refrigerator. These technologies enabled us to downsize the system. Prior to practical use at the RIBF, the HTS SQUID monitor was installed in the beam transport line of the RIKEN ring cyclotron to demonstrate its performance. As a result, a 20 μA $^{40}Ar^{15+}$ beam intensity (63 MeV/u) was successfully measured with a 500 nA resolution. Despite the performance taking place in an environment with strong gamma ray and neutron flux radiation, RF background and large stray magnetic fields, the measurements were successfully carried out in this study. This year, the HTS SQUID monitor was upgraded to have a resolution of 100 nA. We will report the present status of the monitor system.

Although the intensity of a sub-micro-ampere beam can be measured, a limit of a minimum current higher than two orders of magnitude is required for fainter beam measurement. The possibility of fabricating a new HTS current sensor and introducing high-permeability cores into the HTS SQUID through two holes has been investigated[3]. The cores are composed of 80% Ni and Mo, Re and Fe. A test using a simulated beam current shows a 50-fold improvement in gain, when the wire used as the simulated beam was wound directly on the high-permeability cores. However, we could not obtain the simulated beam current signal, when both the HTS SQUID and the HTS current sensor were used. The HTS SQUID sensor plays a role in detecting the beam current, from which we assumed the reason the signal could not be obtained was that the HTS current sensor could not reach a superconducting state. If the critical temperature of the HTS current sensor is lower than that of liquid nitrogen, the HTS current sensor was no longer be in a superconducting state. Then in order to cool the HTS current sensor and the HTS SQUID to below the temperature of liquid nitrogen, we chose a method using the cryostat of the HTS SQUID monitor by exchanging all components inside the cryostat. A new cooling mechanism inside the cryostat was designed and fabricated for these purposes. As a result, the HTS current sensor could reach superconducting state at a temperature of 68 K. On the other hand, because the HTS SQUID was designed to achieve the best performance at the temperature of the liquid nitrogen (77K), it could not operate properly at a temperature of 68K. Therefore, the examination to confirm whether these HTS components achieved high sensitivity is being postponed
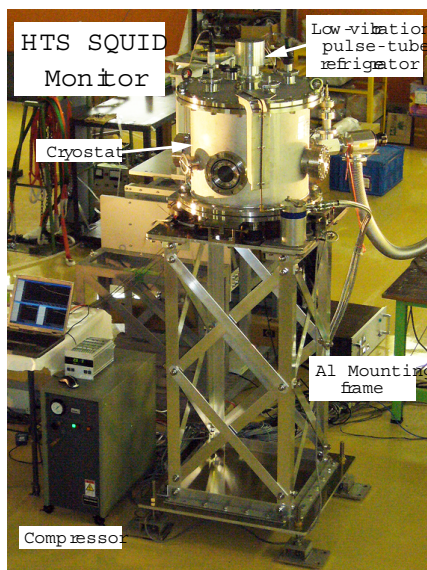
Fig. 1. The HTS SQUID monitor equipped with new HTS SQUID containing a high-permeability core and Al mounting frame was reassembled.
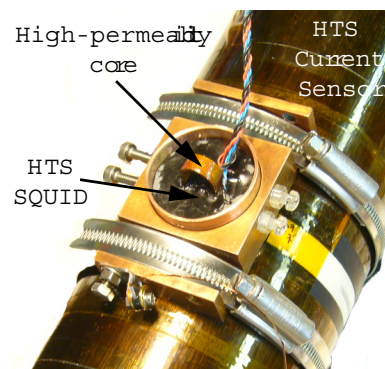
Fig. 2. Photograph of new HTS SQUID with two holes containing high-permeability core.
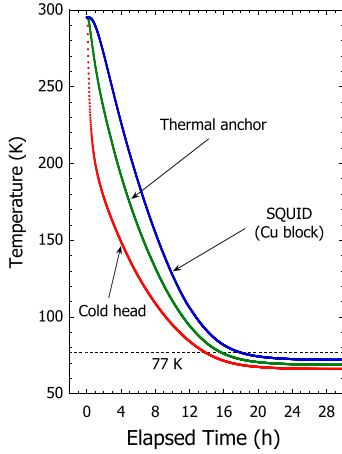
Fig. 3. Cooling processes recorded for over 30 h using silicon diode thermometers.

Fig. 5. Effect of removal of environmental noise by introducing the noise cancellation system.

for the present.

Aiming for a practical use for accelerator operations at the RIBF, we reassembled the HTS SQUID monitor with the new HTS SQUID containing a high-permeability core and an aluminium mounting frame (Fig. 1). The previous frame made of iron was replaced with one made of aluminium with a relative permeability of 1. Figure 2 shows a photograph of the new HTS SQUID with two holes containing the high-permeability core. An HTS magnetic shield and the HTS current sensor, including the HTS SQUID, are cooled by a pulse-tube refrigerator which is a low vibration type and has a refrigeration power of 11 W at a temperature of 77 K. Figure. 3 shows the results of the cooling processes; temperatures of the cold head, the thermal anchor and the Cu block holding the HTS SQUID were recorded for over 30 h using silicon diode thermometers. The temperature of the HTS SQUID was found to reach the temperature of liquid nitrogen (77 K) after 16.5 h. The output voltage of the HTS SQUID controller as a function of the simulated beam current is plotted in Fig. 4. From these measurement

results, the calibration equation obtained is

$$V_s = S_{co} \times I_b \times G/500$$
$$= 46.60 \times I_b \times G/500,$$

where S_{co}, I_b, V_s and G are the coupling efficiency (mV/μA), the beam current (μA), the output voltage of the HTS SQUID controller (mV) and the gain, respectively. A test using a simulated beam current showed a 2-fold improvement in gain, because the coupling efficiency S_{co} of the HTS SQUID monitor was 22.8 mV/μA[1]. The transfer of the magnetic field produced by the simulated beam current to the HTS SQUID was thus improved.

To obtain a better resolution for the measurement, we paid close attention to the reduction of noise. A noise-cut transformer which is completely isolated from the power circuit and not affected by AC source noise was introduced. Furthermore, all instruments were fixed onto a large aluminum plate and the grounds of the instruments were connected to the plate. The signal cables were wired carefully to reduce unnecessary loops as much as possible and all AC lines were covered with braided wires. The design of the noise cancellation system is based on a three-axis Helmholtz cage and feedback control engineering. Three-axis flux-gate sensors are placed near the equipment. A signal is fed through the proprietary controller to a compensation coil, producing precisely calibrated electromagnetic fields. The preliminary result in Figs. 5 (a) and (b) shows the effect of the removal of environmental noise by introducing the noise cancellation system. The data acquisition and control program being written by LabVIEW (National Instruments, Ltd.) is almost complete, but some modification is necessary.

Fig. 4. Plot of output voltage of the HTS SQUID controller as a function of simulated beam current.

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Development of ion beam core monitor

H. Watanabe, S. Watanabe,[*1] R. Koyama,[*2] and M. Kase

A nondestructive ion beam core monitor has been developed to measure the intensity of a beam current. It is particularly useful if one can continuously monitor the ion beam current without interrupting the ion beam. The core monitor has been installed into the RIKEN ring cyclotron output beamline to measure ion beams. We report here the test experiments for nondestructive ion beam monitoring of the cyclotron using a toroidal transformer.

We used a Fast Current Transformer (FCT) manufactured by BERGOZ Instrumentation. The transformer, model FCT-082-05:1-H-INS, consists of a toroidal core made of cobalt-based nanocrystalline and amorphous alloys of 82 mm inner diameter and a five-turn coil wound by the proprietary multithread technique. The multithread winding is a technique of core winding whereby there are few turns around the core. Many parallel wires are wound, clockwise and anticlockwise. The principle of the transformer detector is shown in Fig. 1.
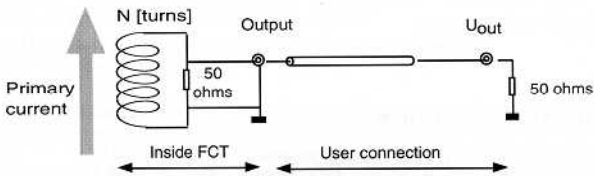
Fig. 1 Schematic diagram of core monitor.

The cyclotron beam is equivalent to a single-turn coil on the primary side of the transformer which induces a magnetic flux in the toroidal core, resulting in an induced current in the secondary coil. The bandwidth of the FCT is 32 kHz – 700 MHz and the typical rise time is 500 ps. The fast response of the detector allows us to observe the higher harmonics of the pulsed beam. Since the bunch width of the cyclotron beam is very short, it generates many harmonics and the higher order harmonics have almost the same power as the fundamental one (36.5 MHz). It is advantageous to observe higher order harmonics, since the ambient noise generally decreases with increasing frequency.

In order for the transformer to measure a current passing through its center, the wall current imaging the ion beam must be diverted around the outside of the device. The beam pipe of 63.5 mm diameter is electrically isolated by a PEEK sleeve of 4 mm width and the FCT is mounted close to the gap. A SUS304 box cover, shown in Fig. 2, forms the FCT electrostatic shielding as well as the electrical

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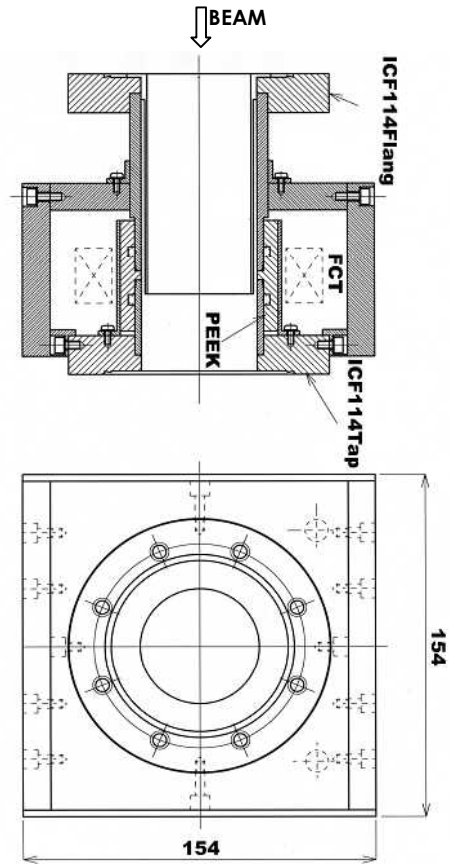
Fig. 2 Mechanical drawing of FCT box cover.

connection between the interrupted beam pipe outside the FCT. The signal from the FCT is sent to a low-noise preamplifier (model SA-230F5) produced by NF corporation. The gain of the preamplifier is 46 dB. The signals obtained from the preamplifier were measured by a spectrum analyzer.
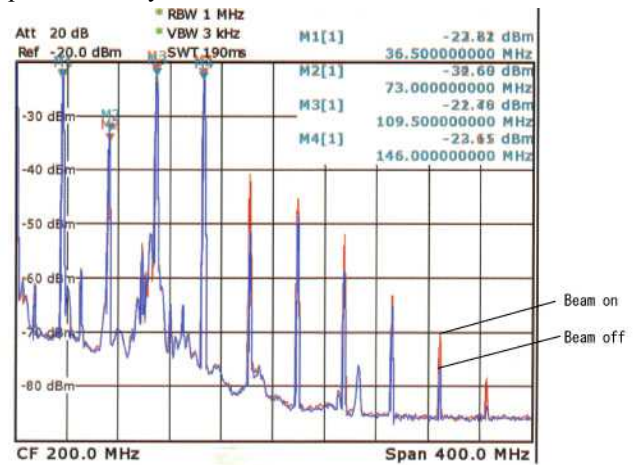
Fig. 3 Power spectrum of ^{48}Ca^{16+} beam of 2.1 euA detected

by the FCT.

The result is shown in Fig. 3. As expected, it is advantageous to observe higher order harmonics, since the ambient noise decreases with increasing frequency. In the future, beam current calibration will be done against a Faraday cup or an additional FCT one-turn coil which a standard current flows through.

Radiation monitoring in the SRC using an ionization chamber.

M. Nakamura, H. Fukuda, K. Yamada and M. Kase

Recently, experiments of the RIBF using the SRC were successfully performed. Nevertheless, beam loss was still a serious problem from the first experiment. To detect the beam loss, we can monitor radiation generated by the interaction of ion beams with accelerator components. However, the radiation is too intense to use the usual detectors. Therefore, we have made an ionization chamber which has quite a simple structure and is solidly built. For this report, we tried to monitor radiation from the SRC during beam extraction using this ionization chamber.

The size of the ionization chamber was 400 mm x 250 mm x 80 mm. Two electrodes were included in the chamber. One electrode was for high voltage (HV), and the other was an ion collector for when radiation enters the ionization chamber. Al plates with 1.5 mm thickness were used for the electrodes. The size of the electrode was 200 mm x 360 mm. These two electrodes were placed at 25 mm interval. The chamber was not built as a vacuum chamber and was filled only with air. Hence, we can detect the ion current of air in this chamber, generated by radiations from the SRC.
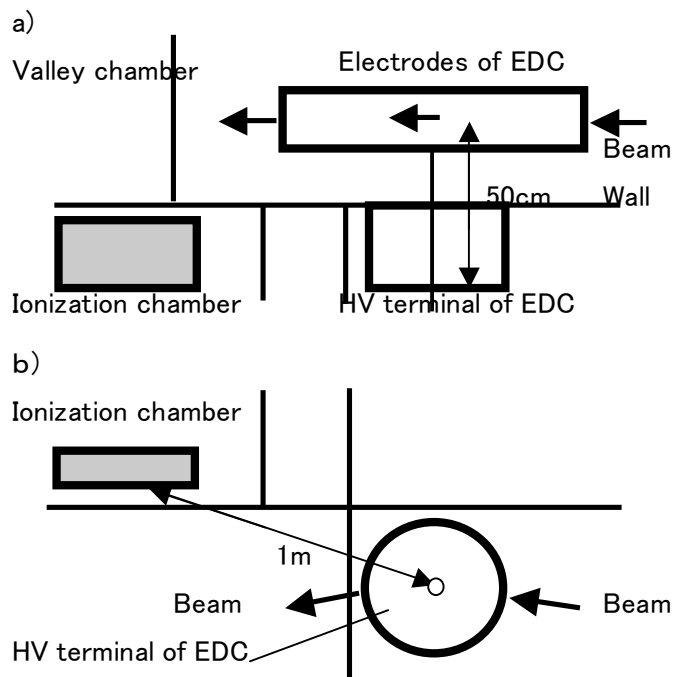
Fig. 1. Location of ionization chamber.
a) Side view. b) View from lower part.

Strong radiation was generated from the septum of the electrostatic deflector (EDC) in the SRC when ion beams were accelerated. The radiation could be strongly observed in the tangent direction of the ion beam. Therefore, the ionization chamber was set on the under side and in the diagonally forward direction of the EDC irradiated by the ion beam.

The location of ionization chamber is shown in Fig. 1 a) and b). The bottom of the HV terminal of the EDC was about 50 cm under the center of the EDC electrodes in the valley chamber. The bottom of the ionization chamber was set nearly as high as the bottom of the HV terminal (shown in Fig.1 a)). The distance between the center of the HV terminal and the ionization chamber was about 1 m (shown in Fig. 1 b)). A few stainless steel walls are present between the electrodes of the EDC and the ionization chamber.

FLUKE 415B was used for the power supply to the HV electrode. An ADVANTEST R8240 digital-electrometer was used for the monitor which transforms current between the two electrodes into voltage. A YOKOGAWA MX-100 was used for data acquisition of R8240 electrometer. Data was captured every 0.1 seconds.

We monitored radiation during RIBF operation from December 5 to 25, 2008. During this operation, ^{48}Ca was accelerated to 345 Mev/nucleon. During this period, 1 kV voltage was always supplied to the HV electrode of the ionization chamber.

Figure 2 a) and b) show examples of the observed data recorded by the data-logger. In these figures, the horizontal axis shows the observation period and the vertical axis shows the voltage monitored by the electrometer. For the vertical axis of these figures, 0.01 V corresponds to 1 nA of current generated between the HV and collector electrodes. In the period shown in Fig. 2 a), the ^{48}Ca beam was accelerated. In the period shown in Fig. 2 b), the ion beam was stopped. The difference between Fig. 2 a) and b) is clearly evident.

In Fig. 2 b), we can not observe any significant signals. On the other hand, in Fig. 2 a), we can observe about 14 nA of current at the maximum value and about 6-7 nA at the average value. These current values correspond to ion generation caused by radiation from the ^{48}Ca beam interacting with SRC components (mainly, EDC).

At this stage, the radionuclide observed by the ionization chamber can not be identified. However, considering the penetrating power of the radiation and ion-pair formation of air, we presume that protons entered chamber and ionized the air. If we assume the ion-current was made by 100 MeV/nucleon protons and ionization loss of protons was about 1 Mev, then 6-7 nA of current could be generated

by about 6×10^6 protons/s.

In this experiment, we were at least able to observe the radiation from SRC using this "simply-made" ionization chamber. By detecting the voltage of the ionization chamber, we can also adjust the RIBF components (mainly, EDC in SRC) at the best location and the beam-loss of RIBF smaller. For the next stage, we plan to set some ionization chambers in RIBF and monitor the beam-loss at these positions simultaneously.

a)
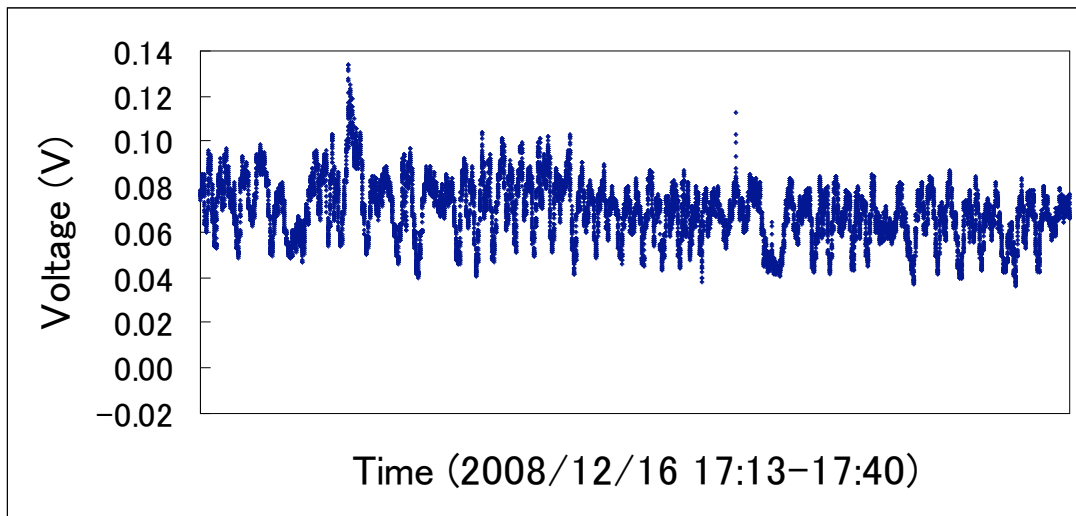
b)
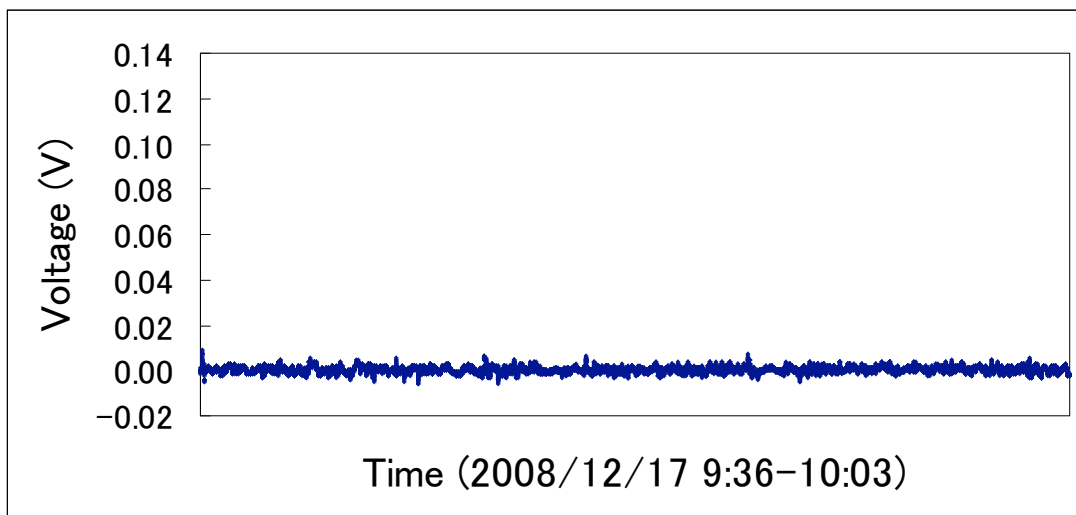
Fig. 2. Observed values of ionization chamber during RIBF commissioning.
   a) ^{48}Ca beam was emitted.   b)   Ion beam was stopped.

Performance Tests of Old Power Supplies in RIBF

Makoto Nagase, Nobuhisa Fukunishi, Seiji Fukuzawa[*1], Eiji Ikezawa, Keiko Kumagai,
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Magnet power supplies of RIKEN Ring Cyclotrons (RRC) and its beam transport system[1] have been used for more than 20 years and we carried over these power supplies in RIBF accelerator complex. As a natural consequence of twenty years operation, we have experienced troubles on these power supplies several times, for example, leakage of water caused by corrosion of cooling water pipe.

As reported in Ref. 2, we started measurements on the accuracies, linearities and stabilities of these old power supplies last year. The main purpose of the measurements is to determine precisely the operation parameters of the magnets. These measurements also give us important information on deterioration of magnet power supplies. Hence, we continued measurements for a part of remaining old power supplies in 2008. Measurements were performed one by one during the periods in which beam services to RIBF users were not scheduled, because stability measurements require long time.

We employed high precision DC current transformers (DCCT)[3,4] in the measurements as reported in Ref. 2. Accuracies of setting currents and long-term stabilities are directly measured by the DCCT employed. The linearity is estimated by increasing or decreasing the current with a constant rate as described in Ref. 2. The observed accuracies and stabilities are summarized in Table 1. The accuracies of the power supplies, which are defined as the differences between the setting currents and the actual output currents observed by the DCCT, were less than 1.7% for all the magnets except for the quadrupole magnet QTD12a. The reason of the observed large difference is that a trimmer potentiometer, which determines the maximum output current, was broken or accidentally moved to the improper value. For other magnets, observed accuracies are within the acceptable level.

Table 1. Summary of accuracy and stability tests performed in 2009.

Magnet exited	Current sensor	Maximum current(A)	Error of current	Stability
QTF41a	Zeranin	151.87	-1.51%	51ppm/5H
QTF41b	Zeranin	151.83	-1.53%	39ppm/5H
QTF41c	Zeranin	151.94	-1.35%	15ppm/13H
QTF01a	Zeranin	151.8	-1.59%	35ppm/13H
QTF01b	Zeranin	151.8	-1.15%	37ppm/7H
QTF01c	Zeranin	151.9	-1.28%	67ppm/7H
DMDA	DCCT	303.75	-1.46%	8ppm/14H
DMAB	DCCT	300	0.12%	16ppm/14H

SWMC	DCCT	303.8	-1.55%	9ppm/8H
QTA01a	Zeranin	263	-0.07%	10ppm/14H
QTA01b	Zeranin	262.8	0.11%	193ppm/14H
DAA1	DCCT	400	-0.28%	13ppm/13H
DMA1	DCCT	303.55	-1.41%	5ppm/4H
QTA11a	Zeranin	151.9	-1.25%	26ppm/13H
QTA11b	Zeranin	151.8	0.02%	189ppm/13H
QTA11c	Zeranin	151.5	-1.00%	17ppm/7H
QTD12a	Zeranin	152	5.29%	173ppm/7H
QTD12b	Zeranin	152.05	-1.04%	45ppm/7H
QTD12c	Zeranin	152.45	-0.34%	79ppm/7H
QTD13a	Zeranin	152.1	-0.41%	19ppm/7H
QTD13b	Zeranin	152.1	-0.14%	39ppm/7H
QTD13c	Zeranin	152	-0.46%	26ppm/10H
QTD14a	Zeranin	151.8	-0.32%	39ppm/10H
QTD14b	Zeranin	151.8	-0.27%	115ppm/13H
QTD14c	Zeranin	151.75	0.00%	152ppm/13H)
QTD15a	Zeranin	152	-0.39%	30ppm/16H
QTD15b	Zeranin	151.81	-0.25%	131ppm/16H
QTD15c	Zeranin	151.81	-0.29%	30ppm/6H
QTD16a	Zeranin	151.82	0.81%	37ppm/6H
QTD16b	Zeranin	151.81	-0.43%	13ppm/16H
QTD16c	Zeranin	151.81	0.79%	23ppm/16H
QTD17a	Zeranin	151.85	-1.57%	21ppm/7H
QTD17b	Zeranin	152.3	-0.43%	49ppm/7H
QTD17c	Zeranin	152.1	-1.40%	35ppm/15H
QTD18a	Zeranin	152	0.14%	54ppm/15H
QTD18b	Zeranin	152.4	-1.64%	11ppm/8H
QTD18c	Zeranin	152.5	-0.72%	33ppm/8H
DAD4	DCCT	400	-0.23%	9ppm/4H
DMD4	DCCT	303.85	-1.53%	6ppm/4H

The stabilities of the power supplies are important for stable operation of RIBF accelerator complex. For dipole magnets (DMDA, DMAB, SWMC, DMA1, DAA1, DAD4, DMD4), the observed stabilities were less than 20 ppm during the measurements. This good performance was a result of the improvement of the current feedback system finished in 2005 as reported in Ref. 5. We adopted DCCT's as current sensors instead of old shunt resistors and also stabilized the temperature of the current-feedback system using Peltier coolers.

For quadrupole magnets, observed stabilities were less than 100 ppm during the measurements except for five quadrupole magnets (QTA01b, QTD12a, QTD14b, QTD15b). The worst one was 193 ppm for 14 hours in the

case of QTA01b. This value is acceptable for RIBF operation, but it means the power supply of QTA01b was very unstable compared with other old power supplies. For closer inspection, results of the stability measurements were shown in Fig. 1 compared with the result of QTA01a. Note that both power supplies are of the same design and were made at the same time. The observed instability for QTA01b may come from deterioration of circuit elements used in the current-feedback system, which is an example of aging problem

Fig. 2 Result of linearity test for QTA01b power supply. The current difference is defined as (Iset – Iobs), Iset implies the setting current and Iobs the observed current measured by the DCCT. In the figure, the excitation current is also shown with the scaling factor of 1/100.

Results of a series of measurements performed in 2007 and 2008 will be used not only for the database of calculation-based operation but also for the basic information which determines a maintenance plan and replacements of deteriorated power supplies in the near future.

Fig. 1 Observed stabilities for QTA01a and QTA01b power supplies.

We also illustrate an example of a linearity test of the QTA01b power supply in Fig. 2. The maximum linearity error observed was 0.6A, which corresponds to 0.23%. It is also within the acceptable level.

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A Linux Cluster with Redundant Design for Accelerator Operation

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The RIKEN RIBF control system is based on Experimental and Industrial Control Systems (EPICS). EPICS Input/Output Controllers (IOCs) control and monitor the devices through Ethernet using the control network. Our control system is consists of many server computers for various purposes; an operational log system based on Zope and PostgreSQL (Zlog)[1], EPICS applications and DNS. Already more than five years have passed since their introduction into our system. In order to use them stably without any serious machine trouble, they should be replaced by new ones periodically. In this paper, we report on the replacement of servers in detail.

To store the EPICS application's programs, we have been using an exclusive server with a RAID 5 system. It has a lot of front-end applications for RILAC/AVF/RIBF operation, such as graphical user interface (GUI) and various measurement programs using channel access (CA). They are centralized to enable software management with ease, and every user connects their client PCs to the application server for beam tuning, beam monitoring and so on. As a result, if this application server has any problems in its control system, all of the accelerators will probably fail to operate. Our Zlog system, however, was implemented on another server computer. The parameters during beam tuning are very important to ascertain the condition of the beam, including essential information for beam analysis. Therefore, we cannot lose any data. For these reasons, we selected the servers which promote reliability, availability, and serviceability (RAS) for the replacement. The requirements of the new system are listed as follows.

* Installation of Redhat Enterprise Linux clones as its operating system.
* We need to consider the load balancing for its heavy system load.
* The service has to work without stopping during the experiment so as not to interrupt it, even if a serious problem occurs on the server, such as disk trouble.
* DNS should be available at any time.

Therefore, we decided to construct the new servers using Linux clustering with a redundant design. Figure 1 shows the system chart in this task.

We configured a new cluster with "active/active" mode for the EPICS applications server. It consists of two servers with load balancing using round robin DNS. The specifications are summarized in Table 1. Generally, round robin DNS is a technique for load balancing in some services, such as web service. In the system, clients can always connect to an available server of servers which share the same hostname. We confirmed that the telnet and ssh client included in CentOS 5.2 exhibit the same behavior as described above.

Besides, user data, for example the home directory, is shared by both the servers using DRBD[2], Heartbeat[3] and NFS. Therefore, they can access the same data in both of the servers, and even if the other server has system failure, they can definitely connect to the alive server. As a result, the redundant system with load balancing was successfully designed and constructed for combination with round robin DNS and the shared user data.
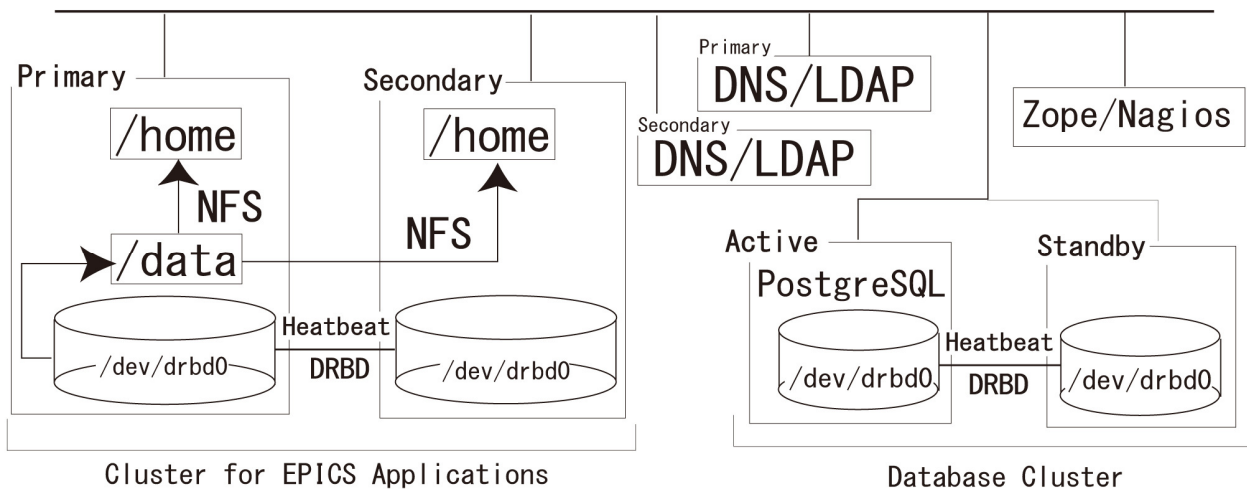
Figure 1. The system chart for this task.

*1 SHI Accelerator Service, Ltd.

OS	Scientific Linux 4.6
CPU	Dual-Core AMD Opteron 2212
Memory	2 GByte
Software	DRBD-0.7, Heatbeat-2.0.0, EPICS base-R3.14.7, MEDM

Table 1. Specifications of the system for EPICS applications.

Zlog is the operational log system developed at KEK for a control system based on EPICS.[1] It consists of following three items; a log monitor server written by Python, a database on PostgreSQL, and the products made by Zope, which is the web application framework for user interface. In operating the system, registered parameters of various devices are monitored and recorded on the database by the log monitor server. Simultaneously, accelerator operators can search, view and input the operation log with the application running within the web browser. In our old Zlog system, Zope, PostgreSQL and log monitor service ran on the same hardware. However, it produced a heavy system load. Therefore, we introduced a new system with one server for Zope and two servers as a cluster for PostgreSQL and log monitor server. The specifications are summarized in Table 2. PostgreSQL cluster is configured with a high-availability (HA) system of "active/standby" using open-source DRBD and Heartbeat. In this HA system, the active node and standby node with RAID 1 system have shared storage using DRBD. Normally, the shared storage is mounted on an active node which runs the PostgreSQL and log monitor service. But if a problem in it is detected by Heatbeat, the standby node mounts the shared storage in place of active node during failover.   At the same time, the services switch over to standby node automatically. As a result, the Zlog system is available to use continuously, even if problems in the system which take time for recovery occur.

Use	HA cluster (Active/Standby)	Zope
OS	CentOS 4.6	CentOS 5.2
CPU	Xeon L5410	Celeron 430
Memory	4 GByte	1 Gbyte
Software	DRBD-0.7, Heatbeat-2.0.0, PostgreSQL-8.0.19, log monitor server (at KEK), EPICS base-3.14.9	Zope-2.10.7, Nagios 3.06

Table 2. Specifications of the system for Zlog

In this task, we introduced two kinds of the clusters for Zlog and EPICS applications, to integrate management of the user environment, such as passwords, guides and login shells. OpenLDAP[4] was installed in the same hardware of primary/secondary DNS for provide LDAP service. As a result of configuring two LDAP servers, the other LDAP server is available for use, even if one of the LDAP servers

has system failure. Generally, when a server encounters a system failure, and stops providing the service, a security alert will be sent by E-mail to the administrator. However, since our network is not connected with the Internet, we cannot receive E-mail. Therefore, open-source Nagios[5] is used to provide the server monitoring system and the administrator can observe alive monitoring using a web browser at any time.

In December 2008, we started launching these clusters after a recovery test. As a result, we succeeded in implementation of RAS clusters for the key service of accelerator operation, constructed at a low-cost using open-source software only for increasing system availability.

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Computer modelling of the nitrogen, oxygen, and proton acceleration in RIKEN AVF cyclotron

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The project to upgrade the AVF cyclotron is being conducted by a collaboration of the Center for Nuclear Study (CNS) of the University of Tokyo, the Joint Institute for Nuclear Research (JINR, Dubna, Russia), and RIKEN. [1] The present study is focused on the formulation of the new acceleration regimes and a beam extraction study in the AVF cyclotron by detailed orbit simulations. The new acceleration regimes include: the expansion of the acceleration energy region of light ions towards higher energies in the existing rf harmonics equal to 2, and the modification of the center geometry for the rf harmonics equal to 1 to make it possible to accelerate protons at several tens of MeV. The current status of the AVF Cyclotron computer model, used for calculations, is described elsewhere. [2,3]

The simulation of injection and acceleration of 7 MeV/nucleon $^{14}N^{5+}$ ion beam was performed in order to obtain better calibration of the simulations vs. the recently conducted experiment.[2] Assessment of losses from the buncher entrance until the initial 20th turn in the cyclotron was carried out. The estimation produced particle losses all along this passage at the level of ~ 66% which corresponds to the measurement of 60-70 %.

The simulation of the $^{14}N^{5+}$ extraction was also carried out by taking into account the 3D modeling results of electromagnetic fields of the extraction system. The extraction system consists of: harmonic coils (HC), an electrostatic deflector (ESD), a magnetic channel (MC) and a gradient corrector (GC). The layout of the extraction system is shown in Fig. 1. Upstream of the ESD the turn pattern showed that some overlapping of the bunches at the neighboring orbits took place. As a result, the beam was extracted with multi-turn extraction as shown in Fig. 2. The transmission efficiency through the ESD was approximately 80 %.

In order to increase the $^{16}O^{7+}$ ion energy, which had been limited to less than about 10 MeV/nucleon due to the voltage available (below 50 kV), up to 11 MeV/u, changing the injection beam phase at the 1st acceleration gap from the original design value of − 30°RF to − 8°RF as well as the corresponding currents of the innermost trim coil was proposed. In this way the energy gain at the 1st turn was increased, permitting the beam to clear the channel immediately after passing through the exit of the inflector. In the actual beam test, 11 MeV/nucleon was succesfully achieved with the presently available voltage of 49 kV.

The first attempt to simulate the acceleration of 60 MeV proton beam in the 1st rf harmonics mode was carried out. Clearly, with the realistic dee voltage of about 50 kV particles would be lost in the channel, since the existing structure of the center region was designed for the 2nd harmonics, not for the 1st. Thus, the substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltages. Nevertheless, to see how protons will be accelerated downstream of the channel, the rf phase excursion during the acceleration until the final energy was simulated using the realistic voltage of 50 kV. The simulation demonstrated a good quality of the magnetic field generated.

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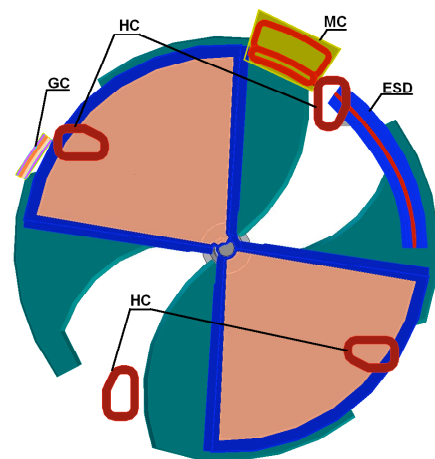
Fig. 1. Layout of the extraction system along with the harmonic coils.
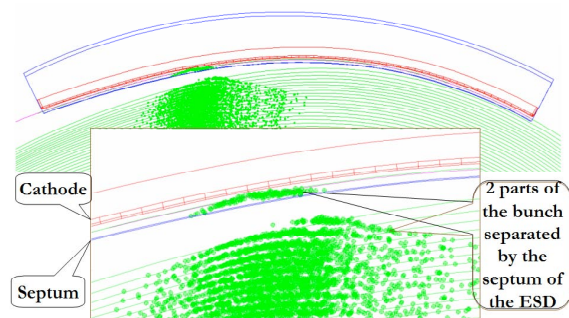
Fig. 2. Simulation of the beam bunches in the extraction region.

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Low Energy Beam Transport of 127 kV U^{35+} on 100 kV Cockcroft

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We are going to construct a new beam line to inject 127 kV U^{35+} beams into the RILAC at RIKEN. The beam line from our new ECR ion source (ECRIS) to the RILAC has two sections, a low energy beam transport (LEBT) section and a medium energy beam transport (MEBT) section. The LEBT section is from the ECRIS to an acceleration tube, and it is on a 100 kV Cockcroft. The MEBT section is from the acceleration tube to the RILAC. The ECRIS has 27 kV higher voltage than the Cockcroft stage. Oxygen is used as supporting gas at the ECRIS. The ECRIS produces U^{35+}, other charged states of U ions, and O ions.

After passing a 90 degree analyzing magnet and a horizontal slit the U^{35+} beam is separated and goes into the acceleration tube. The acceleration tube connects the 100 kV Cockcroft stage and ground level. After the acceleration tube, the 127 kV U^{35+} beam is transported through 13.6 m MEBT up to the RILAC.

The LEBT consists of the 28 GHz superconducting ECRIS, a solenoid, a positioning box, a steerer upstream, the 90 degree analyzing bending dipole, a steerer downstream, a horizontal and vertical slit, diagnostics, and the acceleration tube (Fig. 1). It is

stream from the bending dipole exit.

We used FEMM[2], IGUN[3], OPERA and KOBRA[4] codes for LEBT simulation. FEMM is a 2D electric field and magnetic field software. IGUN simulates plasma sheath of an ion source under cylindrical extraction voltage. OPERA is a 3D electric field and magnetic field software. KOBRA simulates 3D trajectory of ions under electric and magnetic fields, including space charge effect. The Solenoidal field of ECRIS and following solenoid was calculated by using FEMM. IGUN was used from the plasma electrode to the 2nd extraction electrode, with 100% space charge effect of total ion beam current 10 emA. We assumed that the ion current of the supporting gas O has the same ratio as RIKEN 18GHz ECRIS data[5]. KOBRA was used from the 2nd extraction electrode to the slit. This area was treated with 20% space charge effect, and the total ion beam current in simulation is 2 emA. The amount of space charge effect in the area is an unknown factor. It has been estimated from 1% to 20% by several groups[1,4]. The 3D magnetic field around the bending dipole was calculated with OPERA. The calculated 3D magnetic field was imported into the KOBRA simulation.

Fig. 1. Beam line of U^{35+} on 100 kV high voltage terminal. Acceleration tube connects the terminal and the ground.

1.4 m from an ECRIS plasma electrode to the bending dipole entrance. This dipole has a bending radius of $\rho = 510$ mm, point to point focusing capability and sextupole components the same as the Venus type at LBNL[1]. The Horizontal slit position is 1.02 m down-

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Fig. 2. Horizontal emittance diagram at 1020 mm after the analyzing dipole. U^{36+}, U^{35+} and U^{34+} are in order from left.

By using the emittance diagrams at the slit are shown in Fig. 2 and 3, we can distinguish U^{35+} from other charged states of U ions. We are going to use this LEBT for uranium ions Fall in 2009 with a 18 GHz microwave source. From this measurement we will find the real amount of space charge effect. We can provide reasonable feedback to optimize our future LEBT, which will be constructed in FY2010.
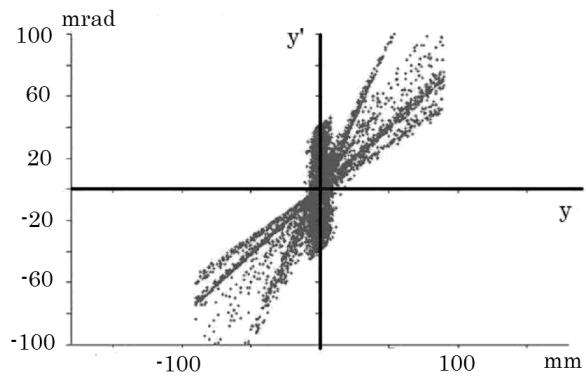
Fig. 3. Vertical emittance diagram at 1020 mm after the analyzing dipole.

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Space Charge effects in the RILAC II

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A new 28GHz superconducting ECR ion source has been constructed mainly to increase intensity of the uranium beam. The ion source is designed to have as large a plasma volume as 1100 cm^3 [1, 2] and expected to produce U^{35+} ions at an intensity of more than 15 pµA, which is necessary to obtain 1 pµA beams from the SRC. This new ECR will take all the succeeding accelerators and beam transport lines to a space charge dominant regime, especially the front end section, which should be carefully looked at again to avoid emittance growth caused by space charge forces. The RILAC II, which is now in design, should allow efficient accelerations of ion beams from the powerful new ion source in order to avoid the emittance growths caused by their space charge forces. In this paper, preliminary results of the beam dynamics simulations for the RILAC II using TRACK codes [3] will be reported with brief discussions.

Figure 1 shows a plan for the new injector RILAC II which is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as ^{84}Kr^{13+}, ^{136}Xe^{20+} and ^{238}U^{35+}, up to an energy of 680 keV/nucleon. It consists mainly of the SC-ECR, an RFQ linac based on the four rod structure, a low energy beam line (LEBT) between extraction from the source and entrance to the RFQ and a drift-tube linac (DTL) based on three quarter-wavelength resonators (QWR) [4]. Using the TRACK code, we simulated beam dynamics in the LEBT, RFQ and DTL.

The LEBT, before charge selection, consists of an extraction region, a glaser solenoid focusing lens, and a 90 degree bending analyzing magnet for charge selection. The bending radius and edge angle of the
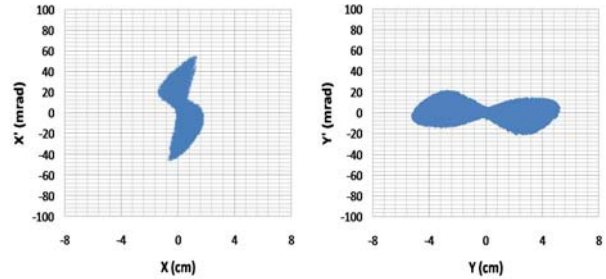
Fig. 2: Emittance plot of U35+ at the end of the LEBT in the case of 50% neutralization of the space charge forces.

bending magnet are selected to be 510 mm and 27 degree, respectively, to provide double focusing. First, the separation of U(34+), U(35+) and U(36+) at the selection point was checked at the 0 mA limit, showing good separation of the three charge states. However, more realistic simulations should include space charge forces from not only uranium ions themselves, but also the other ion species extracted from the ion sources. U(35+) and five O(2+, 3+, 4+, 5+, 6+) ions were simultaneously transported through the LEBT, assuming different neutralization factors by electrons from residual gases. The ion beam was assumed to consist of 0.5 mA of U^{35+}, 1.4 mA of O^{2+}, 2.5 mA of O^{3+}, 2.6 mA of O^{4+}, 1.9 mA of O^{5+} and 1.6 mA of O^{6+}. The calculation results show that emittance of the U beam grows with large distortion as the neutralization factor decreases. For example Fig. 2 shows an emittance plot in the horizontal and vertical direction in the case of 50 % neutralization. Fig. 3 summarizes the emittance versus the neutralization factor.
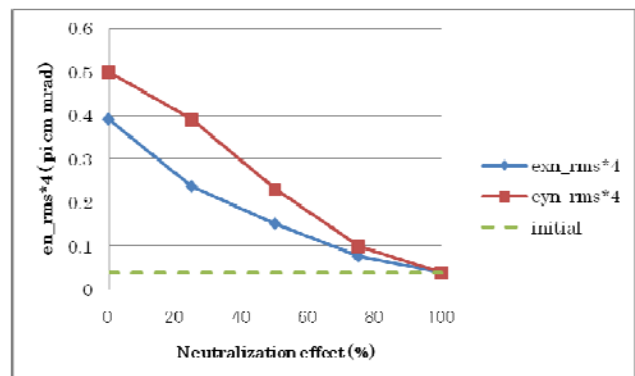
Fig. 3: Normalized emittance in the horizontal and vertical direction at the exit of the LEBT is listed versus neutralization factor of the space charge forces.

Fig. 1: A plan of the new injector RILAC II.
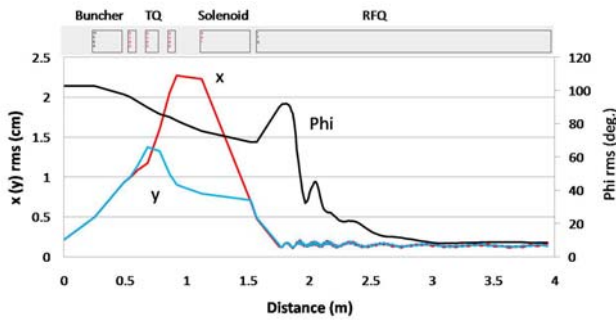
Fig. 4: Beam dynamics from the selection slits in the LEBT to the exit of the RFQ.

After the selection of the U^{35+} the ion beams are transported to the entrance of the RFQ. The components and the position of the section in the LEBT are shown in Fig. 4. They are designed by intensive study using TRANSPORT by Sato [6]. The field strength of each element was tuned so as to fit twiss parameters of the beams to the matching conditions at the entrance of the RFQ using TRACE3D [7]. A beam buncher is also installed in this section to make the beam bunch with 18.25 MHz which is the fundamental frequency of the RIBF accelerator complex. The voltage and position of the buncher should be optimized so as to maximize efficiency of beams trapped in the proper separatorix because the RFQ is operated in the second harmonic of the 18.25 MHz. Beam dynamics in the part of the LEBT after the selection slit and RFQ were simulated using TRACK code in order to estimate the trap efficiency in the cases of 0.0A and 0.5mA, changing the voltage of the buncher. An input file of its vane structure for TRACK was made by DESRFQ [8] code. Fig. 4 shows a result in the case of 0.5mA. Transmission and trap efficiency are listed in Table 1. Fig 5 shows bunch shapes which give the maximum transmission in the cases of 0.0mA and 0.5 mA. Even distorted bunch shape due to space charge forces can gives an efficiency of more than 80%.

Beam dynamics in the DTL were also simulated. The model of the DTL consists of the rf gaps and drift spaces with beam rebunchers and two quadrupole
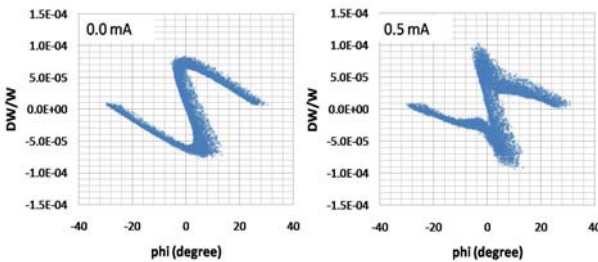
Fig.5:   Longitudinal emittance plots at the entrance of the RFQ   in the case of   0.0 mA and 0.5mA

	Transmission (%)	Trap efficiency (%)
0.0 mA	68.9	86.7
0.5 mA	50.2	81.1

Table 1: Transmission and trap efficiency of the ion beams from the selection slit to the exit of the RFQ.

doublets. Fig. 6 shows the simulation results in the case of 0.5 mA. The results for the both cases of 0 mA and 0.5 mA do not differ so much, indicating that 680keV/u is high enough to avoid the emittance growth caused by their space charge forces.

In summary, we simulated beam dynamics in the LEBT, RFQ and DTL for RILAC II using the TRACK code. Simulations for LEBT before the selection slit show that the neutralization factor of space charge force largely depends on emittance at the slit. Trap efficiency in the proper separatorix of the RFQ is not affected by the space charge force in the LEBT so much. We should, however, take care whether emittance growth at the exit of the RFQ has an affect on the transmission in the succeeding accelerator. This is under analysis. Simulations for the DTL showed that space charge effect in the DTL is not so large.
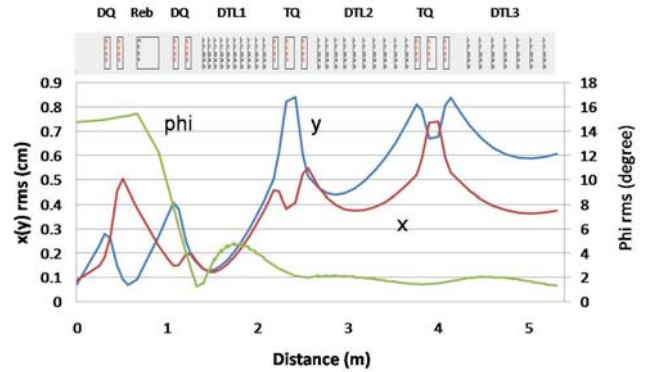
Fig. 6:   Beam dynamics of the DTL with short MEBT including a re-buncher.

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Medium Energy Beam Transport System from the New Superconducting ECR Ion Source to RILAC

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The challenging superconducting coils for the new 28GHz ECR ion source [1] were successfully excited in 2008. [2] The ion source is designed to have as large a plasma volume as 1100 cm^3 , so as to produce U^{35+} ions at an intensity of more than 15 pµA, which is necessary to obtain 1 pµA beams from the SRC. Beam tests will start in 2009. This new powerful ion source will be put on a 100kV deck so that extracted beams from the source can be directly injected to the RILAC, skipping the RFQ in the uranium acceleration in order to enjoy the high intensity uranium beams as soon as possible. The existing acceleration scheme requires low frequency operation of the RFQ pre-injector at 18.25 MHz and extraction voltage as low as 5 kV in the uranium acceleration. High power beams accelerated by the extraction voltage of 5 kV steadily grow up due to their space charge forces in the low energy transport line. This direct injection to the RILAC of extracted ion beams accelerated by the high voltage of 127 kV is expected to suppress the emittance growth in the low energy beam transport system because in general space charge effect is proportional to the cube of ion velocity. Furthermore this plan is easy for us to be realised because we can use the room for the former injector to the RILAC, 450kV Cockroft-Walton as shown in Fig. 1. Also, the existing operation will not be interrupted for long periods due to installation.

This project requires making the LEBT (Low Energy Beam Transport system), reformation of the HV terminal, the acceleration tube and the MEBT (Medium energy transport system), including the beam diagnosis and the vacuum system. The main component of the LEBT is the analyzing magnet

Table 1: Initial parameters and matching condition used in the simulations. Normalized emittance εn, twiss parameters α an β are listed in each section.

(a) MEBT Kinetic energy: 18.676 keV/u

Ion: U35+

	εn (cm mrad)	α	β(cm/rad)
Horizontal	0.041542	-0.6635	340
Vertical	0.041542	-0.6635	340

(b) Matching condition with at the entrance of RILAC

Ion: U35+

	εn (cm mrad)	α	β(cm/rad)
Horizontal		0.5743	22.69
Vertical		0.0872	132.3

which has the function of correcting aberrations in the horizontal and vertical direction. It was successfully fabricated after the study of the beam dynamics in the LEBT including space charge forces. [2] The reformation of the HV terminal including replacement of the insulating support rods, started before installation of the superconducting magnets for the 28GHz ECR ion source. A prehab room, which is necessary for the radiation control, was made after the installation of the ion source. Ion beams from ion sources accelerate by 100 kV through the acceleration tube, the detailed design of which is in progress. The

Figure 1: A plan of the new injector.
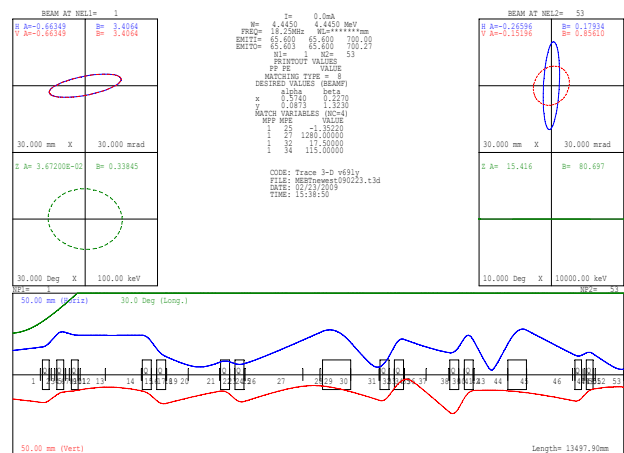
Figure 2 Beam envelope in the MEBT. Emittance plots at its entrance and exit are also shown in the upper parts.
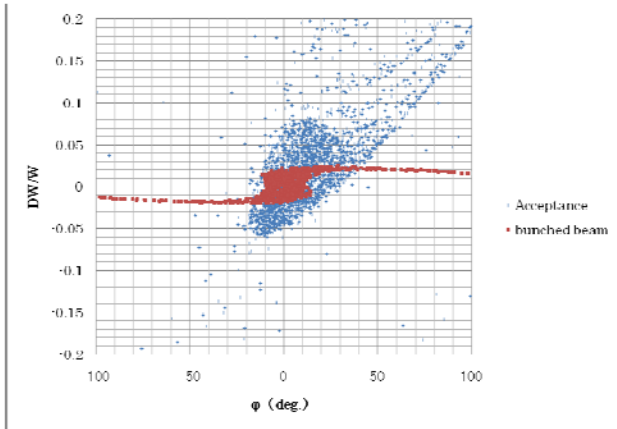
Fig.3 Longitudinal emittance plots at the exit of the MEBT with longitudinal acceptance of the RILAC.

detailed designs of MEBT are also in progress following the study of the beam dynamics [3,4].

The latter part of this report concentrates on the simulation of the beam dynamics in the MEBT and RILAC using TRACK [4]. Table 3 summarizes initial conditions at the entrance of the MEBT and matching conditions at the entrance of the RILAC.

After the ion beams from the LEBT are accelerated in the accelerating tube, they are transported to the entrance of the RILAC through the MEBT. In the MEBT DC beams from the ion source are bunched in the two 1st harmonics bunchers so that the RILAC can accept the beams effectively. The model consists of 13 quadrupole magnets and two 60 degree bending magnets. The first buncher is placed before the two bending magnets which allow doubly achromatic beam transportation and the last buncher is installed about 1 m before the entrance of the RILAC. This configuration is finalized following intensive study of beam dynamics using TRANSPORT [3]. The field gradients of the quadrupole magnets were obtained from the simulation using TRACE 3D [5] so that the Twiss parameters of emittance ellipses at the entrance of the RILAC match those of the acceptance ellipses.

Fig. 3 shows bunched phase plot from a simulation result using TRACK code. Longitudinal acceptance of the RILAC is also shown in the figure indicating that about 51% of the DC beams can be accepted by the RILAC. The RILAC consists of six variable-frequency cavities. The model treated the motion in the rf gaps with the impulse approximation; with sinusoidally varying voltage, it was assumed the ions gained kinetic energy at the midgap where they were exposed to the rf defocusing force at the same time. The validity of this approximation in such a low energy region should be checked by comparison with results using more realistic models. The model also includes the quadrupole magnets embedded in the drift tubes and inserted between the tanks. Fig. 4 shows the simulation results from the entrance of the MEBT to the exit of the RILAC in the case of 0mA. Total transmission efficiency of about 50% seems to be determined not by transversal but longitudinal acceptance.

In summary, beam dynamics simulations in the RILAC with MEBT were carried out using TRACK in order to check the matching conditions at the entrance of the RILAC and longitudinal acceptance in the RILAC. Simulation results in the case of 0 mA are consistent with the former studies on beam dynamics in the RILAC. Simulations including space charge forces in the case of non zero current are in progress.

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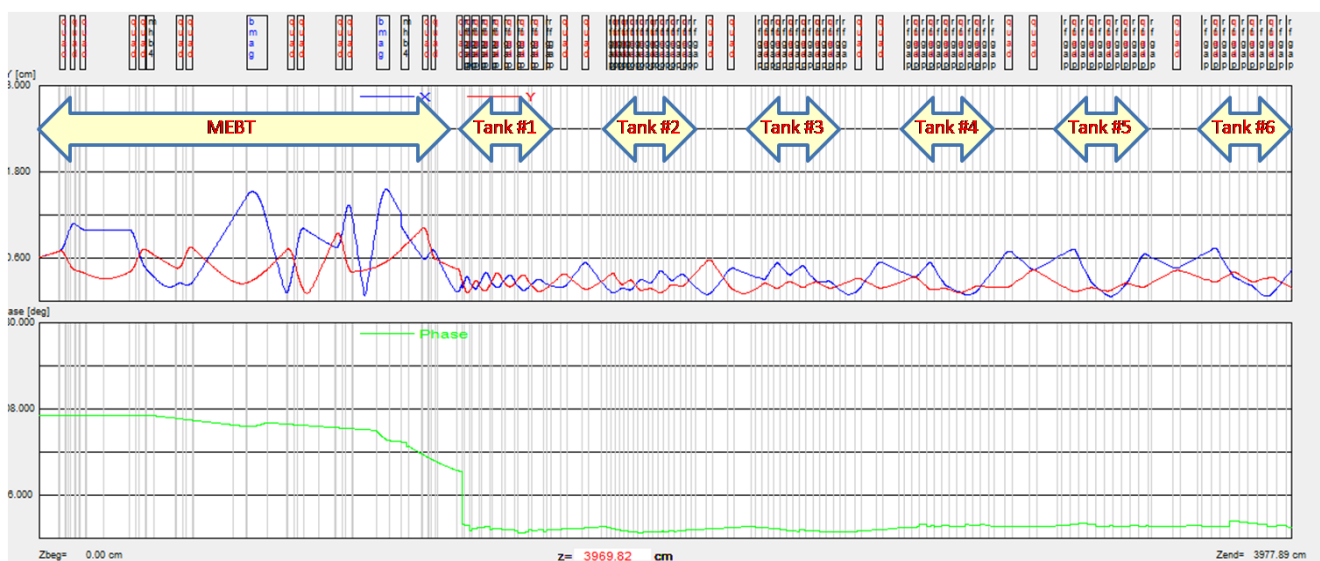
Fig.4 A simulation result for MEBT+RILAC.

Emittance measurement of a singly charged heavy ion beam produced by laser for use in RHIC-EBIS

Takeshi Kanesue,[*1] Jun Tamura,[*2] Masahiro Okamura[*3]

A Laser ion source (LIS) is a candidate for the primary ion source of the RHIC EBIS which is a future heavy ion injector for the Relativistic Heavy Ion Collider and NASA Space Radiation Laboratory.[1] A low charge state, low emittance and high ion yield laser ion source using a high power Nd:YAG laser with a defocused laser beam is being studied as the primary ion source for the RHIC EBIS.[2] During RHIC EBIS operation, the primary ion source provides singly charged ions and the RHIC EBIS enhances the charge state of ions. Since this EBIS will be capable of changing ion species on a pulse by pulse basis, the primary ion source is also required to change ions on a pulse by pulse basis.

A laser ion source produces ions by pulsed high power laser irradiation onto a solid state target. Ion species can be changed by controlling the laser path to other target species. The target is rapidly heated, vaporized and becomes a plasma called laser ablation plasma. Then the plasma expands adiabatically perpendicular to the target surface. Generally, a laser ion source is used for highly charged high current ion production with minimal laser spot size to achieve higher power density on the target. However, a laser ion source can be optimized for singly charged, low energy ion production suitable for providing seed ions for charge bleeding by decreasing the power density. Since the properties of laser produced plasma are different for different species, laser power density for singly charged ion production should be verified experimentally for each atomic species.

We measured plasma properties of C, Al, Si, Fe, Fe, Ta and Au targets using the second harmonics of Nd:YAG laser (532 nm wave length, up to 0.5 J / 6 ns). The relationship between power density and plasma total current was measured while changing laser power density by controlling laser spot size on the target. Results of this experiment show that singly charged ion dominant beams can be produced from all of the species mentioned above. For example, over 95 % of ions are singly charged ions below 9×10^8 W / cm^2 in case of Au. The details of this experiment are given in [3].

The emittance of the Au beam was measured using a pepper pot emittance monitor[4]. Laser power density and extraction conditions were chosen to achieve sufficient particles as a primary ion source for this experiment based on singly charged ion production experiment. A laser power density of 1.7×10^8 W / cm^2 was used for this experiment. The plasma drifting length and extraction aperture diameter were 1.60 m and 18 mm, respetively. The estimated number of particles, peak current and pulse duration were 1.9×10^{11}, 0.28 mA and 110 μs, respectively.

The experimental set up was modified for emittance measurement experiment. A 25.4 cm long extraction column with a movable intermediate electrode was placed 1.6 m away from the target. A gridded lens, [5] which is an electrical lens to focus the ion beam, was located downstream of the insulator. A pepper pot was located at a distance of 2.4 m from the target. The target chamber including the target and plasma drift chamber was biased to 16 kV to extract ions from the plasma.

Normalized RMS emittance was 0.025 π mm mrad after optimization of the gridded lens voltage, intermediate electrode position and voltage. This value is comparable to the hollow cathode ion source (HCIS) used as the primary ion source for the RHIC-EBIS test stand, although the current from the HSIS was typically several tens of micro amperes which is about an order of magnitude lower than that of LIS. Figure 1 shows the measured horizontal phase space diagram processed by software developed for the pepper pot. It was found that the laser ion source can be used as a primary ion source for the RHIC-EBIS.
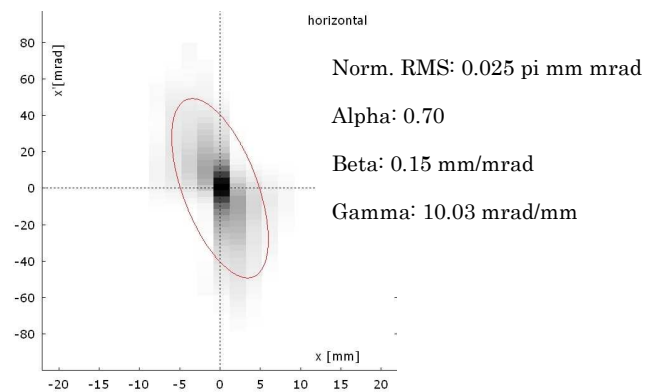
Fig. 1. Measured horizontal phase space using Au target with 16 kV extraction voltage

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Preparation for Beam Analysis Experiment for EBIS-RFQ Linac

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We have prepared for an upcoming beam analysis experiment for a new RFQ linac which is part of an Electron Beam Ion Source (EBIS) based RHIC preinjector. The EBIS-RFQ (100 MHz, 4-rod cavity) was designed to accelerate Au^{32+} beam from an input energy of 17 keV/nucleon to 300 keV/nucleon. In the new preinjector system, multiple charge state ions are simultaneously injected into the RFQ.

To evaluate the output beam properties, we simulated a multiple charged ion beam acceleration using a particle-mesh method for space charge force calculation. At each step in time, this solves the Poisson equation from charge densities assigned to grid points from the particles, and then moves the particles. The RF electric field from vane electrodes was derived from the two-term potential function and the field in the radial-matching section was from the four-term potential function. Figure 1 shows a simulation result (longitudinal phase space at the end of the RFQ vane). Here Au^{31+}(3mA, 17*31/32 keV/nucleon), Au^{32+}(4mA, 17keV/nucleon) and Au^{33+}(3mA, 17*33/32 keV/nucleon) are injected into the RFQ. Then more than 98 % of the particles are accelerated to the designed output energy of 300 keV/nucleon, while unaccelerated particles maintain the velocity at the initial injection velocity. The bunch length is 60 degree (13 mm). There will be 1000-4000 bunches per pulse since the pulse width of a beam from EBIS is 10-40 us. The bunch shape will be measured with a fast Faraday cup installed just behind the RFQ. The ion current is consists of particles which survived transversely (accelerated and unaccelerated).
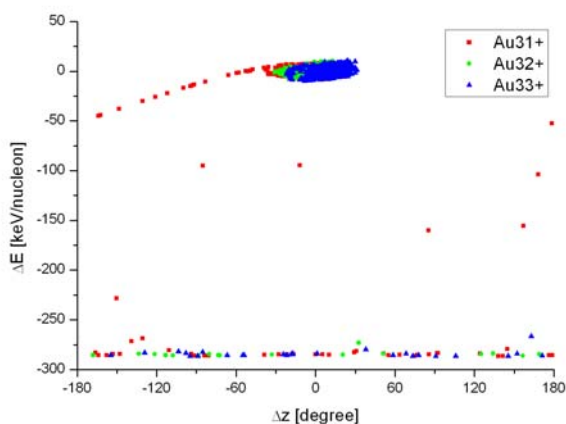
Fig. 1. Longitudinal phase space at the end of the RFQ vane. 180 degree is the length of 3.8 cm. dE = 0 corresponds to the kinetic energy of 300 keV/nucleon.

The beam analysis line shown in Fig. 2 was designed using the TRACE-3D program. There are 5 quadrupole magnets to control the beam condition and a dipole magnet to separate different charge state ions. Ion current only from accelerated particles can be measured with the fast Faraday cup installed between the quadrupole and dipole, since unaccelerated particles cannot pass through these quadrupole magnets. To separate Au^{32+} and the others using this dipole magnet (B <= 1 T, 45 degree deflection), more than 1 m distance from the magnet is necessary. In case of lighter species like Fe and Cu, less flight distance can be applied.
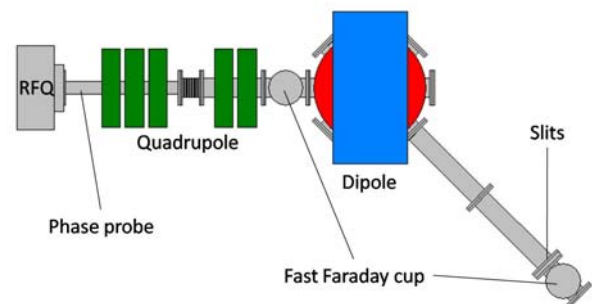
Fig. 2. Experimental set up of beam analysis line for EBIS- RFQ.

We measured resonant frequency of the RFQ cavity with a network analyzer by adjusting two tuners. When we pushed the tuner into the cavity, resonant frequency increased linearly. The full frequency range was from 100.574 MHz to 100.761 MHz. When we pushed one tuner into the cavity, the electric field near the tuner is decreased and the field near the other tuner is increased.

We will continue to improve the RFQ simulation code. This measurement will be completed by the end of March 2009.

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7.   Instrumentation

Status of the BigRIPS and ZeroDegree Project

T. Kubo, K. Kusaka, T. Ohnishi, K. Yoshida, A. Yoshida, N. Fukuda, M. Ohtake, Y. Yanagisawa, H. Takeda, N. Inabe, D. Kameda, K. Tanaka, H. Sakurai, T. Motobayashi, and Y. Yano

This report describes the status of the major research instruments in the RI beam factory (RIBF), such as the BigRIPS in-flight separator,[1,2] the ZeroDegree spectrometer[3] and the high-resolution beam line for the SHARAQ spectrograph.[4] The BigRIPS and ZeroDegree were successfully commissioned in May 2007 and November 2008, respectively, while the high-resolution beam line is in the final stage of construction. Commissioning of the high-resolution beam line is scheduled for March 2009, together with SHARAQ.

Figure 1 shows a schematic layout of the major research instruments at RIBF along with the RIBF cyclotrons. The BigRIPS separator is composed of 14 superconducting triplet quadrupoles (STQ) having large apertures and 6 room-temperature dipoles, which are labeled as STQ1-14 and D1-6 in Fig.1. There are seven focuses indicated as F1-7. One of BigRIPS's major features is large acceptances, which were achieved by using the large-aperture quadrupoles. Thanks to this feature, not only projectile fragmentation of various heavy ions but also in-flight fission of uranium beams can be efficiently used as a production reaction for RI beams.

Another important feature is its two-stage structure. The first stage includes the components between the production target (F0) and F2, while the second stage spans those from F3 to F7. The section from F2 to F3 works as a matching section. This feature allows deliver of tagged RI beams as well as use as a two-stage tandem separator. In the former mode, the first stage is used to produce and separate RI beams with an energy degrader, while the second stage works as a spectrometer to analyze and identify those RI beams. The momentum resolution of the second stage is high enough to identify RI beams without measuring total kinetic energies, even if some of them are not fully stripped. In the two-stage separator mode, an energy degrader is used at both stages to further purity the RI beams.

In each focus, there is a focal-plane chamber to accommodate various beam-line devices and detectors used for diagnostics and particle identification (PID). The PID scheme is based on the ΔE-TOF-Bρ method in which trajectory reconstruction is used to improve the resolution. The primary beams stops at a high-power beam dump located at the first dipole D1. The first stage is surrounded by radiation shields which weigh about 7000 tons.

The RI-beam delivery line following the BigRIPS is used not only to transport RI beams to experimental setups, but also as a forward spectrometer named ZeroDegree. It consists of 9 STQs and 2 dipoles, labeled as STQ15-23 and D7-8 in Fig.1. The magnets of ZeroDegree have essentially the same design as those of BigRIPS. The focuses are indicated as F8-F12. The section from F8 to F11 forms the ZeroDegree spectrometer, while that from F7 to F8
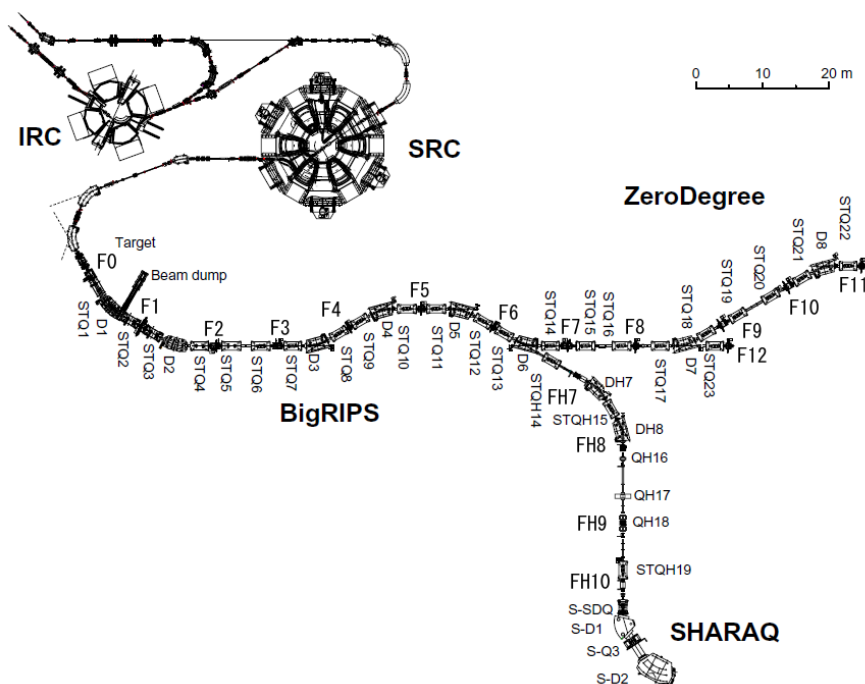
Fig.1. Schematic layout of RI Beam Factory in 2009.

works for matching. In each focus, there is a focal-plane chamber which accommodates beam-line detectors and devices similarly to BigRIPS. A secondary target is placed at F8, when the beam line is used as the ZeroDegree spectrometer for reaction studies with RI beams. The ZeroDegree analyzes and identifies projectile reaction residues, often in coincidence with γ-rays which are measured by a γ-ray array detector surrounding the target. Depending on the experimental requirements, the ZeroDegree can be operated in different optics modes, such as achromatic modes and dispersive modes. Figure 2 shows a recent photograph of the ZeroDegree spectrometer.

Fig. 2. Photograph of the ZeroDegree spectrometer.

The high-resolution beam line consists of the existing part (the section from F3 to D6) and the new part leading to the SHARAQ spectrograph (the section from D6 to the SHARAQ target position). The new part is composed of 2 room-temperature dipoles, 3 STQs, and 3 room-temperature quadrupoles, which are labeled as DH7-8, STQH14-15, STQH19, and QH16-18 in Fig. 1. The focuses are indicated as FH7-10. This beam line can be operated in a dispersive mode with high resolution, so that the dispersion matching conditions can be attained at the SHARAQ focal plane, allowing high-resolution measurement using the SHARAQ. Figure 3 shows a recent photograph of the high-resolution beam line under construction.

Fig. 3. Photographs of the high-resolution beam line.

Commissioning of the BigRIPS was carried out in May 2007 with a ^{238}U beam at 345 MeV/u, and performance of the BigRIPS was successfully tested. High PID performance was obtained thanks to the trajectory reconstruction. Then a search for new isotopes was made using the ^{238}U beam as a series of experiments, and the very neutron-rich new palladium (Z=46) isotopes ^{125}Pd and ^{126}Pd were observed for the first time, although the uranium beam intensity was far from the goal and the observation time was

short. The discovery demonstrated not only the performance of the BigRIPS separator, but also the great potential of the RIBF. The details are described in Ref. 5.

Commissioning of the ZeroDegree was carried out in November 2008 with a ^{238}U beam at 345 MeV/u, and the ion optics and PID performance were successfully tested for different ion-optics modes. Then we revisited the search for new isotopes using a ^{238}U beam with ~40 times larger intensity than in 2007, which demonstrated the overwhelming RI-beam production power at RIBF. Figure 4 shows the PID plot obtained using the BigRIPS. We were able to identify more than 20 new isotopes in the Z=30~50 region and also more than 10 new isomers. In particular we were able to observe the further neutron-rich palladium isotopes ^{127}Pd and ^{128}Pd, which means that we have reached an N=82 magic number nucleus. Furthermore ^{128}Pd is said to be one of the key nuclei in the r-process path. In December 2008 the ZeroDegree was used, for the first time, for a series of full-dress RI-beam experiments, where an intense ^{48}Ca beam was employed for the production of RI beams and important results were obtained for very neutron-rich exotic nuclei.
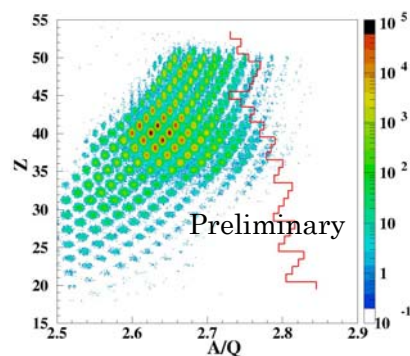
Fig. 4. Particle identification plot for fission fragments produced by ^{238}U+Be reaction at 345 MeV/u.

The BigRIPS cryogenic plant, which is used to cool STQ1-5, suffered from an oil-contamination problem which caused a decrease in cooling power after an operation period of two months or so. This problem has been solved by upgrading the oil removal unit of the compressor and fully cleaning up the cold box.

We plan to fully install quick-release mechanisms using the pillow seal system in the beam line of the BigRIPS first stage in summer 2009. This will facilitate maintenance under high residual radiation.

More detailed reports on the project are given elsewhere in this progress report.

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Commissioning of ZeroDegree spectrometer

T. Ohnishi, T. Kubo, K. Kusaka, K. Yoshida, A. Yoshida, M. Ohtake, N. Fukuda, H. Takeda, D. Kameda, K. Tanaka, N. Inabe, Y. Yanagisawa, H. Watanabe, H. Otsu, Y. Kondo, Y. Gono, H. Sakurai, T. Motobayashi, H. Baba, T. Ichihara, Y. Yamaguchi, M. Takechi, S. Nishimura, H. Ueno, A. Yoshimi, T. Nakao [*1], M. Matsushita [*2], K. Ieki [*2], Y. Mizoi [*3], N. Kobayashi [*4], K. N. Tanaka [*4], Y. Kawada [*4], N. Tanaka [*4], S. Deguchi [*4], Y. Satou [*4], T. Nakamura [*4], K. Yoshinaga [*5], C. Ishii [*5], H. Yoshii [*5], N. Uematsu [*5], Y. Shiraki [*5], T. Sumikama [*5], J. Chiba [*5], E. Ideguchi [*6], S. Ota [*6], A. Saito [*6], Y. Sasamoto [*6], T. Uesaka [*6], S. Shimoura [*6], T. Yamaguchi [*7], T. Suzuki [*7], T. Moriguchi [*8], A. Ozawa [*8], T. Ohtsubo [*9], M. Famiano [*10], A. S. Nettleton [*11], B. M. Sherrill [*11], S. Manikonda [*12], and J. A. Nolen [*12]

An RI-beam delivery line[1] named the ZeroDegree spectrometer is located after the BigRIPS separator.[2] The main purpose of this spectrometer is to analyze particles emitted by reaction of the RI beam with secondary targets. The ZeroDegree has different optics modes to handle various experimental condition requirements such as large angular acceptance or high momentum resolution for secondary-reaction experiments. In 2007, BigRIPS was successfully commissioned and the first experiment with BigRIPS was performed.[3] After the improvement of optics calculation using the results obtained from the commissioning BigRIPS, we commissioned ZeroDegree using a uranium beam and RI beams in November 2008.

Figure 1 shows a schematic top view of BigRIPS and ZeroDegree. The labels STQn, Dn and Fn indicate the position of superconducting quadrupole triplets, room-temperature dipoles and focal planes, respectively. ZeroDegree consists of six superconducting quadrupole magnets (STQ17–22) and two room-temperature dipole magnets (D7–D8). The designs of these magnets are same as those of BigRIPS. In commissioning of ZeroDegree, three modes were examined: an achromatic large-acceptance (LA) mode, a dispersive mode, and a dispersive high-resolution (HR) mode. Their specifications are summarized in Table 1.

A ^{238}U beam was accelerated to an energy of 345 MeV/nucleon using an accelerator complex consisting of the linear accelerator RILAC and the four cyclotrons RRC, fRC, IRC, and SRC.[4] The production targets were 7-mm-thick Be and 1.5-mm-thick Pb. Beam current was 1.9×10^9 particle/sec on average. Fission fragments were collected and analyzed using BigRIPS. Tagged fragments were supplied to the RI delivery line

including ZeroDegree. During the commissioning experiment, the $B\rho$ values of BigRIPS were set to 7.2 Tm and 7.4 Tm in order to examine the $B\rho$ dependence of the properties of the optics. At the beginning of the beam line (F8) of ZeroDegree, a 2-mm-thick Pb secondary target was installed. Projectile fragments from the secondary target were analyzed and identified using ZeroDegree. To evaluate the performance of ZeroDegree more clearly, data without the secondary target at F8 was also obtained.

Particle identification in ZeroDegree is same as that in BigRIPS. It is performed using the measured $B\rho$, energy loss (ΔE), and time of flight (TOF). TOF was measured using two plastic scintillation counters placed on the first (F8) and final (F11) focal planes with a central flight length of 37 m. Thickness of the scintillation counters was 0.2 mm and their effective area was 100×100 mm^2. In the dispersive mode, the F11 focal plane changes to the dispersive focal plane. A long plastic scintillation counter with an active area of $200 \times 100 \times 0.2$ mm^3 was installed at F11 to cover the wide position distribution in the dispersive and the dispersive HR modes. To measure ΔE, an ionization chamber[5] was installed at F11. The effective area of the ionization chamber was 240×150mm^2. For precise $B\rho$ measurement in the achromatic LA mode, the trajectory of the fragments was reconstructed from the positions and angles measured at two position-sensitive PPACs[5] at the achromatic focal plane (F8) and two more at the dispersive focal plane (F9). For the other modes, two PPACs located at F11 instead of at F9 were used. Ion-optical transfer matrices calculated using the code COSY INFINITY[6] were used in the reconstruction. The $B\rho$ of each fragment was determined from the reconstructed trajectory, the magnetic fields measured using NMR probes, and the magnetic field-map data of dipole. To confirm the particle identification performed at ZeroDegree, delayed γ rays from isomeric states in some of the products were measured using three clover-type high-purity germanium detectors located at F11.[7]

Fission fragments, produced in the ^{238}U+Pb reaction in BigRIPS with a $B\rho$ setting of 7.395 Tm and a momentum acceptance of $\pm 3\%$, were delivered to ZeroDegree without the secondary target at F8.

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*12 Argonne National Laboratory
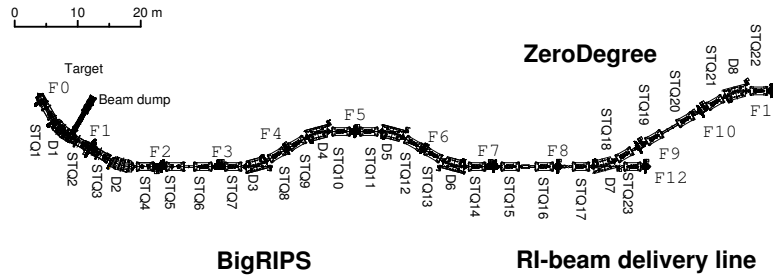
Fig. 1. Schematic top view of BigRIPS separator, RI-beam delivery line and ZeroDegree spectrometer. The labels STQn, Dn and Fn indicate the position of superconducting quadrupole triplets, room-temperature dipoles and focal planes, respectively.

Table 1. Basic specifications of the ZeroDegree spectrometer depending on the optics mode.

Mode	Achromatic large-acceptance mode	Dispersive mode	Dispersive high-resolution mode
Angular acceptance(mr)			
Horizontal	90	40	30
Vertical	70	60	30
Momentum acceptance(%)	6	4	2
Momentum resolution($P/\Delta P$)	1240	4100	6400

These fragments were identified again using ZeroDegree. Fig. 2a) and 2b) show two-dimensional plots of the atomic number Z versus the mass-to-charge ratio A/Q identified using ZeroDegree in the achromatic LA mode and dispersive mode, respectively. The typical relative root-mean-square (rms) resolution for Z and A/Q was 0.5% and 0.09% for the achromatic LA mode, and 0.6% and 0.076% for the dispersive mode. Since the calculated optical matrices are slightly different from the measured matrices, the resolution, especially the A/Q resolution, is worse than the expected values.

In summary, we commissioned ZeroDegree and measured its performance such as ion optics and particle identification capability. Further data analysis is in progress to extract more detailed features of ZeroDegree, for example, the performance of particle identification with the secondary target.

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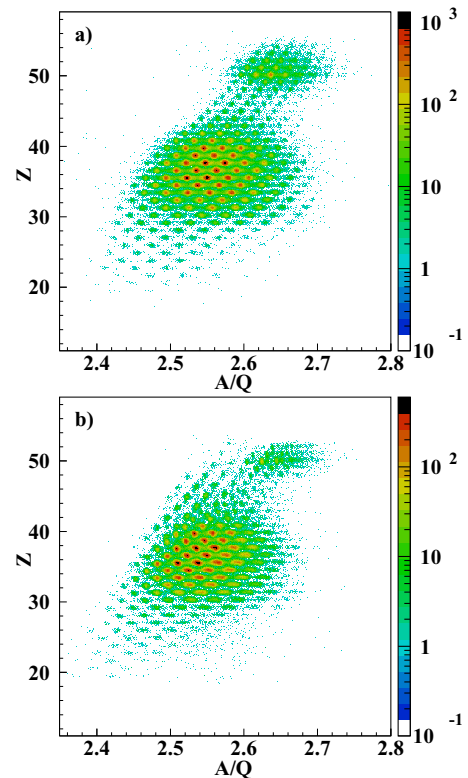
Fig. 2. Two-dimensional plot of Z versus A/Q identified using ZeroDegree. Fission fragments were produced in the ^{238}U+Pb reaction at BigRIPS with a $B\rho$ setting of 7.395 Tm and a momentum acceptance of $\Delta P/P=\pm3\%$. The vertical axis is Z, while the horizontal axis is A/Q. Upper a) and lower b) figures show the results obtained with the achromatic large-acceptance and the dispersive modes, respectively.

Beam intensity monitors for BigRIPS separator

Y. Yamaguchi, A. Yoshida, Y. Yanagisawa, K. Tanaka, T. Ohnishi, and T. Kubo

[scattering particle, beam current]
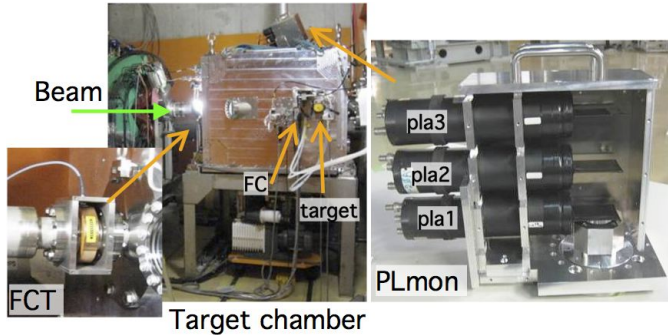
Fig. 1. Setup of beam intensity monitors at production target chamber.

To monitor the primary beam intensity on a production target of the BigRIPS separator[1], a scattered particle PLastic MONitor (PLmon), a Fast Current Transformer (FCT)[2] and a Faraday Cup (FC) are installed at the production target chamber (Fig. 1). The FCT is fixed at the entrance beam duct, the FC is movable in front of the target and the PLmon is mounted on the top of the chamber at an angle of 120 degrees from the beam axis and 68 cm away from the target. The PLmon consists of three layers of plastic scintillators of 1 mm thickness, which detect scattered light charged particles from the target. The PLmon is designed for low intensity beams up to a few 100 electric nano-Ampere (enA). For higher intensity than that, the FCT should be used. These two detectors can continuously monitor the beam current during experiments. They should, however, be calibrated using the beam current measured by the FC at the beginning of each experiment. Here, we report the beam test results of these detectors.

The spectra of the PLmon were measured for three patterns of beam and target combinations as sum-

Table 1. The combinations of beams and targets for the PLmon measurement. The beam energy of U and Kr was 345 MeV/u and those maximum beam intensities are listed in units of enA. The count rate of the PLmon in single mode and in triple coincidence mode are also listed.

Pattern	Beam (enA)	Target	single/coin.
1	^{86}Kr^{31+} (50)	Be (12 mm)	350k/68k cps
2	^{238}U^{86+} (2.3)	Be (5 mm)	1.2k/0.2k
3	^{238}U^{86+} (2.2)	Pb (1.5 mm)	1.2k/1.2k

marized in Table 1. They were measured under the triple coincidence condition of three layer scintillators. Figure 2 shows the energy–loss correlations between two scintillators in the PLmon. Although the beam is different, the spectra of pattern 1 and 2 looks similar. On the other hand, though the beam is the same, the spectra of pattern 2 and 3 look different. In pattern 3, it detected not only protons and deuterium but also tritium, ^{3}He and/or ^{4}He. This means that the kind of the scattered charged particle depends on the target material rather than the element of the incident beam. The energy distribution of these charged particles was measured roughly by inserting energy absorber plates made of aluminum in front of the first (pla1) scintillator. The minimum measurable energy was 10 MeV for protons, which was determined by a Kapton vac-
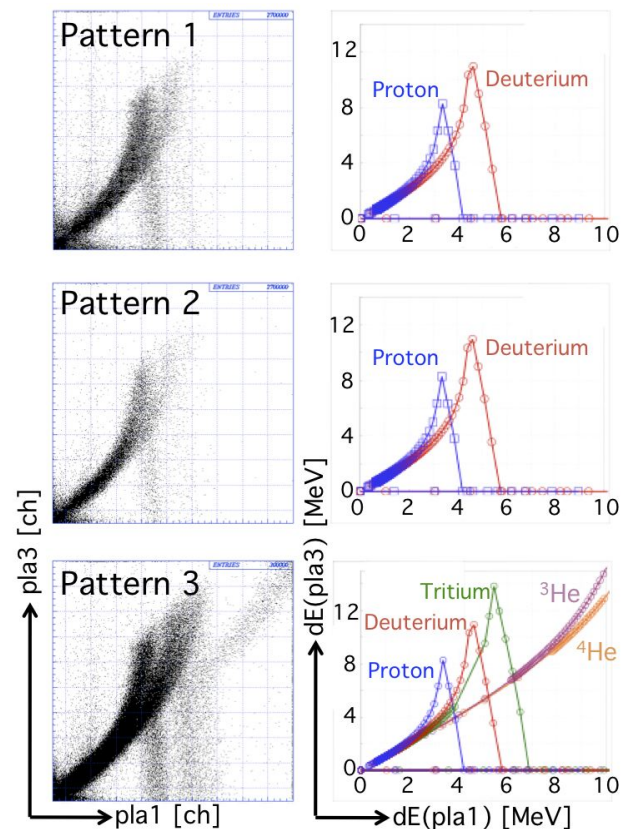
Fig. 2. Energy–loss correlations between the first (pla1) and the third (pla3) scintillator. Measured spectra (left side) and energy–loss calculations (right side) are compared for three patterns of beam and target combinations.
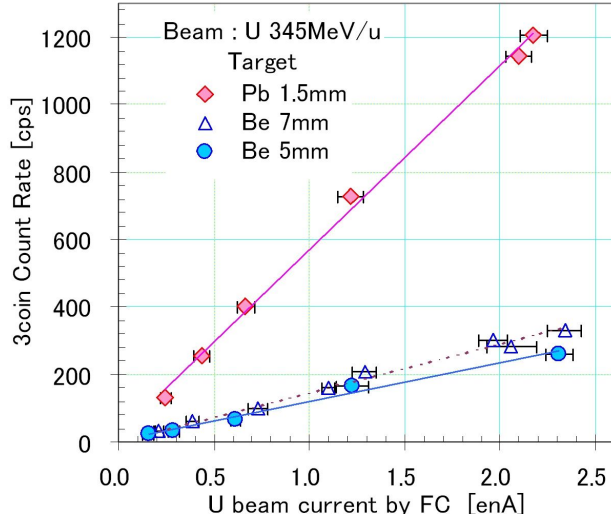
Fig. 3. Target dependence of the triple coincidence count rate of the PLmon.

Fig. 5. Correlation between the FCT signal and the beam current measured by the FC.

uum foil of 40 μm thickness placed at the mounting flange. We expected the energy of scattered protons in this backward angle to be up to a few 10 MeV, using a simulation code PHITS[3]. It was, however, confirmed that protons with an energy of about 100 MeV were also scattered. However the rate of such high–energy protons is less than 1/10. This discussion is still on-going. Figure 3 shows that the count rate of the PLmon had good linear correlation with the measured beam current using the FC in the range of 0.1 enA up to the maximum current listed in Table 1. The count rate also had a target dependence. The Pb target has

a 3 times higher count rate than that of Be target. The PLmon was working without any problem in a few 10 enA. However, when the beam intensity was higher than a few 100 enA, the backgrounds increased and the scattered charged particle was not able to be counted precisely.

The FCT signal was measured using a high intensity beam of ^{48}Ca^{20+}, 350 MeV/u. Figure 4 shows a comparison of measured FC current and FCT signal. The FCT signal is measured using a lock-in amplifier in the unit of volts. The FCT signal had good linear correlation with the measured FC current in the range of a few 10 enA up to 3 eμA. Its lower limit was determined by its noise level of 3.7 μV. It is important to reduce the noise as much as possible. Figure 5 shows that the FCT signal had good linear correlation with the measured beam current using the FC in the range of a few 10 enA up to 3 eμA. The slope parameter 3.3 μV/μA was slightly different from the nominal value of the FCT coil of 5 μV/μA.

Fig. 4. Changing the ^{48}Ca beam current, the FC beam current (upper) and the FCT signal (middle and lower) were compared. The background noise level of the FCT was 3.7 μV.

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Manipulation and performance of ionization chambers for BigRIPS experiments

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Ionization chambers used for BigRIPS experiments give information proportional to energy loss ($\Delta E \propto \frac{Z^2}{\beta^2}$) of the flight particles. In order to deduce the Z information, it combined with Time Of Flight(TOF) information which is derived from a pair of fast response detectors such as plastic scintillators. In FY2008, two ion chambers were prepared and in effect operated for two sets of BigRIPS experiments using ^{238}U and ^{48}Ca primary beams in November and December respectively.

Configuration of the ionization chamber

Each ionization chamber[1] consists of the chamber itself, which contains inner gas, and a set of electrodes. The electrodes consist of 12 anodes sandwiched between 13 cathodes. The cathode electrodes are equivalent to ground voltage level. The original objective in reference[1] was to tilt the electrodes up to 30° from perpendicular geometry which has been expected to prevent ionized pairs from recombining along drift directions. At this point, we selected the perpendicular setup as shown in fig. 1 where the electrodes were penetrated from around 90°. We have estimated a drawback of ΔE resolution by the recombination effect being smaller than those of noise on signal from the electrodes or stability of circuits downstream. Effective
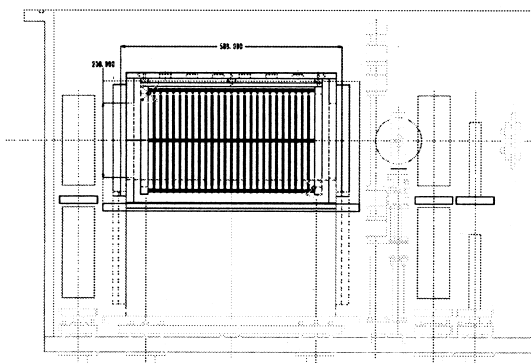
Fig. 1. Side view of the ionization chamber located at the F7 focal point on the BigRIPS beamline.

areas of electrodes are 232 mmϕ for the F7 ionization chamber and 260×170 mm^2 with edging by R10 for the F11 ionization chamber respectively. We describe them F7IC and F11IC following this. The electrode distances between the anode plate and the cathode

plate are 17 mm for F7IC and 20mm for F11IC. Path length for F7IC is 586 mm and that of F11IC is 660 mm, where the curve shapes of entrance and exit windows are neglected. Kapton foils are used for each of these windows. The thickness of the windows will be mentioned in the following paragraph. The geometry of F7IC is restricted by the boundary conditions interior within the F7 vacuum box.

The electrodes both for the anodes and the cathodes in F7IC are formed by a single face layer of evaporated aluminized Mylar with 4 μm mounted on a frame. The other face was evaporated using a machine in the B52 room with evaporation thicknesses being 30 nm. The electrodes for F11IC were formed with a similar configuration but with a layer of aluminized Mylar of 2 μm. Finally, it has been found that the electrode can be formed with a layer of Mylar film with 2 μm thickness. Material thickness for F7IC is summed up to 0.109 g/cm^2 when used with P10 gas (Ar 90%+CH$_4$ 10%)) at 650 Torr of pressure. Material thickness for F11IC is summed up to 0.136 g/cm^2 when used with P10 gas at 760 Torr of pressure.

Performance of the ionization chamber

Signals from two neighboring anode plates were bundled inside the ionization chamber and 6 ch analog signals were read out. Each channel was followed by a pre-amplifier, CANBERRA 2004 for F7IC and TEN-NELEC TC-170 for F11IC. Pre-amplifier outputs were shaped by fast shaping amplifiers CANBERRA 2024 and acquired by peak hold ADCs for the recording of data. The pulse height from each channel was averaged over both arithmetically and geometrically and was found to be not so different from each other in the conditions for the last experiments. Figure 2 shows the result of the experiment for new isotope search in fission fragments from the ^{238}U primary beam. The horizontal axis denotes a raw pulse height without a β correction while data are eliminated by just a narrow time range which corresponds to one isotope at each Z. Each peak represents the identified atomic number Z. In the on-line analysis of the ^{238}U beam experiment, 5σ separation was achieved in the Z $\simeq$ 30 for F11IC. As for F7IC, several mis-handlings worsened resolution to 3σ separation. In the on-line analysis for the ^{48}Ca beam experiment, 5σ separation was achieved in Z $\simeq$ 8 for both F7IC and F11IC. For standard operation of ICs, a lower limit for the Z identification was found to be around $Z = 5$ where the Z identification was realized even with plastic scintillators. A tolerance against beam intensity more than several of 10^4 Hz has not yet

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been measured in the sequence of the experiments.

Gas handling

It is very important to obtain constant pressure inside the ICs as pulse height is proportional to the amount of gas material along beam paths and energy loss of the penetrating particles should not fluctuate with gas pressure. The gas handler consists of a self-feedback system 640A (MKS Co.) with mass flow meter, baratron gauge, needle valve and rotary pump. The gas handler is the same with that for PPACs but the pressure range of the 640A is modified to cover up to 1000 Torr. Constant pressure had been achieved by applying a feedback of 640A. It should be noted that 640A actually has the two functions of open/close the valve and reducing conductance. The latter function responds quite quickly to deviation of pressure while the former function seems to require additional time, e.g. several minutes. As a result, pressure fluctuations may occur when 640A operates with opening and closing the valve.

In the experiment using the ^{238}U beam, both the gas handlers for F7IC and F11IC operated by the open/close mode where comparatively amounts of gas flowed. Gas pressure fluctuated with a triangular wave form with time constant and repetition of order of 10 minutes. Therefore, output signal fluctuations were observed to be a maximum of 2%. Acquired data should be analyzed by correcting the alterations of pulse height for the experiment. This fluctuation might occurred according to difference of range of flow rate between the mass flow meter in the 640A and other devices including a gas regulator on gas bottles and the setting of the needle valve.

In the experiment in December, the gas flow quantity was quite limited by the needle valve and the solution was found so much that 640A does not enter the open/close mode but reduces only the conductance.

As a result, less than 2 Torr deviation was realized in comparison with more than 15 Torr for the previous experiment. So, we no longer require any treatment in
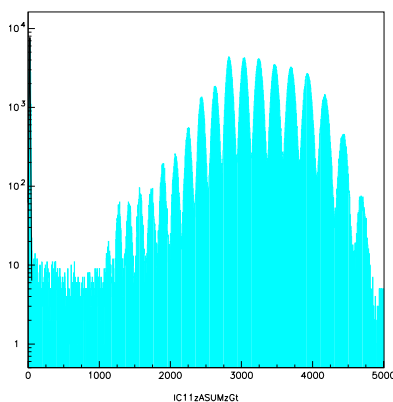
Fig. 2. Z identification by F11IC. Horizontal axis represents Z but the scale is arbitrary. The peak around channel 3900 corresponds to Z=32.

time chasing analysis in the experiment.

Tore window incident

F11IC was prepared in August 2008 as the experiment had been scheduled in October at first. In the preparations, a tear in the vacuum tight window occurred in F11IC.

For shortage of gas substitution time, F11IC can be drawn to a vacuum and filled with high purity gases. For this method, entrance and exit windows were made of Kapton film with more than 75 μm of thickness. This thickness is relatively thick even though F11IC is located within atmospheric conditions rather than a vacuum as in the case of F7IC. To confirm whether this process is possible and feasible, vacuum tests were carried out twice without any devices inside the chamber. The vacuum acheived was less than 1 Torr sufficient to the substitution method. At that time, the Kapton sheet with 75 μm completely withstood any cracks or tears with the pressed surface shapes being fixed. After the tests, the devices inside F11IC were installed again and F11IC was set on the F11 focal plane. The exit window tear occurred when the vacuum in the chamber was drawn down to approximately 180 Torr. All 25 electrodes inside the chamber were also torn. A picture taken just after the incident is shown in figure 3. In addition, a plastic scintillator just downstream of F11IC was destroyed. We have not yet confined the reason of the problem. Possible reasons would be the rectangular shape of the exit window, the surface fixed shape after repeated testing, or possible defects in other source. The entrance and exit window of both F7IC and F11 IC were replaced with 150 μm Kapton film after the incident. F7IC is used in vacuum
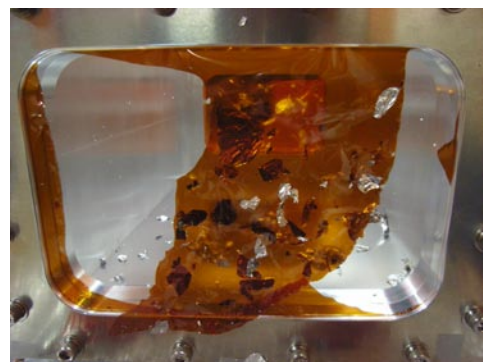
Fig. 3. Torn exit window just after the incident.

circumstance with the windows playing an important role to contain the gas inside. The same kind of incident would destroy not only the detectors inside the F7 vacuum chamber but also the vacuum system consisting of TMP, RP and vacuum gauges. Therefore, it is recommended the window film be replaced at each time experiment is conducted.

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SHARAQ Project — Progress in 2008 —

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Construction of the SHARAQ spectrometer[1] and the dedicated high-resolution beamline[2] are coming to the final phase. This article provides an overview of progress in 2008.

1 Spectrometer

The SHARAQ spectrometer (Fig.1) consists of three quadrupole (Q1, Q2, and Q3) and two dipole (D1 and D2) magnets. All the magnets were installed in summer of 2007.
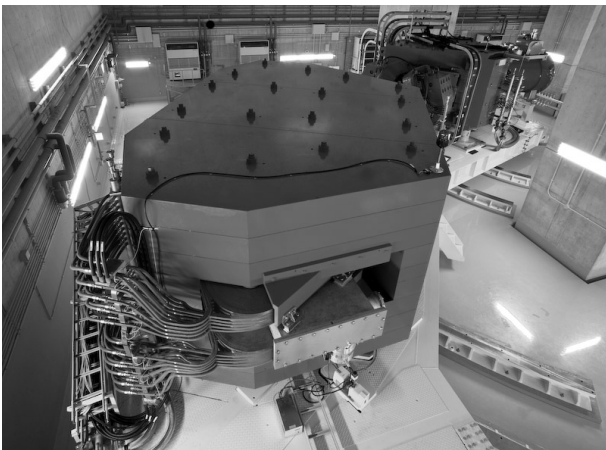
Fig. 1. Photograph of the SHARAQ spectrometer as of April 2008.

Magnetic field distributions of dipole magnets were measured in 2008. Accurate and precise knowledge of the magnetic field is extremely important for high-resolution ion-optical analysis in RI beam experiments. We have measured the magnetic field distribution for a large area of 1.3 m^2 each at the exit of D1 and the entrance and exit of D2. To scan this large area within a reasonable time, we used the search coil method[4] for measurement. In addition to medium plane measurement, we also collected data for the off-medium plane of $y=0$–85 mm, where y denotes distance from the medium plane. The details of the measurement are described in Ref.[3]. Ion-optical calculation based on the measured field mapping will be used to predict transport matrix elements of the SHARAQ spectrometer.

Now that it is equipped with focal plane vacuum chambers, the SHARAQ spectrometer is almost ready to accept heavy ion beams.

2 High-resolution beam line

Based on the detailed design in Ref.[2], we have finalized specifications of beamline devices, including two normal conducting dipole magnets with a 30° bending angle, vacuum chambers for beamline detectors, vacuum pumps, and DC power supplies. Four normal conducting quadrupole magnets and one superconducting triplet quadrupole magnets (STQ) were recycled. One of the normal conducting quadrupoles was renovated to enlarge the bore radius from 150 mm to 180 mm to enable acceptance of large-emittance secondary beams from BigRIPS. Construction of the beamline started in summer of 2008 and will be completed by the end of February 2009.[5]

Several beamline modes should be prepared to enable versatile use of the SHARAQ spectrometer. We have investigated a new large momentum acceptance mode[6], in addition to dispersion matching and high-resolution achromatic modes for high-resolution missing mass measurements. In the large momentum acceptance mode, the beamline allows beam momentum spread of $\Delta p/p =2\%$, which is about 6 times larger than that in the dispersion matching mode. Experiments with low-intensity rare isotope beams can be efficiently conducted in the large acceptance mode.

3 Focal plane detectors

Cathode readout drift chambers will be used as tracking detectors at the final focal plane of the SHARAQ spectrometer. They have an effective area of 550 mm (H) ×300 mm (V) to cover the focal plane. To minimize multiple scattering effects, operation at gas pressures as low as $P_{gas} \sim$3–5 kPa was investigated through simulations with GARFIELD. Based on the results, We examined expected performance of the CRDCs and specified the requirements for drift voltage, pad pattern, and readout electronics were specified.[7] The CRDCs were fabricated in collaboration with the GANIL group and were transported to RIBF in December 2008.

4 Beam-line detectors

Thin tracking detectors working under a beam intensity of higher than 1 MHz are key devices in high-

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resolution experiments with SHARAQ. They are used for tuning the beamline and tagging beam trajectories during measurements. Energy straggling and multiple scattering in the detector materials must be kept small so that the energy resolution of $\Delta E/E < 1/7500$ and angular resolution of $\Delta\theta$ <1 mrad required in SHARAQ experiments are not ruined. Low-pressure multiwire drift chambers (LP-MWDC) were developed as the beam-line detectors.[8] In 2008, the detectors were irradiated with an accelerated α-beam with an energy of 8.8A MeV.[9,10] The energy deposit of the alpha particles is same as that of a 200-MeV/A nitrogen beam which will be used in a future experiment at SHARAQ. The results clearly demonstrated that LP-MWDC with an isobuthane gas should work under a pressure as low as 10 kPa. It was also found that further improvements in the electronics are required for better determination of the energy loss of particles.

5 Towards commissioning

The commissioning of the SHARAQ spectrometer and the beamline is scheduled for March 2009. All the devices including magnetic systems and detectors will be tested there. One of the most important issues to be investigated in the commissioning run is evaluation of higher-order aberration of the beamline. A challenge of the SHARAQ project is to achieve high-resolution magnetic analysis with momentum resolution of $p/\Delta p = 15000$ and angular resolution of $\Delta\theta$ =1 mrad for large-emittance RI beams. Precise knowledge of higher order aberrations is especially important. We are planning to measure all the geometric and chromatic terms, causing image and angular broadening larger than 1 mm and 1 mrad. Efforts are being made to establish a method with which we can disentangle each contribution from the complicated phase space distributions.

Acknowledgement

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Magnetic field measurement for the dipole magnets of the SHARAQ spectrometer[†]

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[Fieldmapping, dipole magnet, spectrometer]

The SHARAQ (Spectroscopy with High-resoluation Analyzer and RadioActive Quantum beams) spectrometer is a high resolution magnetic spectrometer designed for radioactive isotopes (RI) beam experiments at the RI Beam Factory (RIBF)[1].

The SHARAQ spectrometer can analyze particles with magnetic rigidity of 1.8 - 6.8 Tm, corresponding to an energy of 40 - 440 MeV/nucleon for $A/Z = 2$ particles. It is designed for momentum and angular resolutions of $\delta p/p \sim 1/15,000$ and $\delta\theta \sim 1$ mrad, respectively. The magnetic composition of the spectrometer is three quadrupole and two dipole magnets. The first dipole magnet (D1) is placed between first quadrupole doublet (SDQ) and singlet quadrupole (Q3) magnets.

The D1 and D2 dipoles have 230 mm and 200 mm gaps, respectively. They have maximum central fields of 1.5 Tesla. The bending radii are 4400 mm and bend angles are 32.7° in the D1 magnet and 59.6° in the D2[2,3].

The beam transfer matrices describe how an ion's motion changes as it travels through the element. Thus, knowledge of transfer matrices requires precise and accurate information of the magnetic field data in the elements. The field data was intended to be used in the input parameters for COSY[2].

The precision and accuracy goal of the mapping process was 0.1 mT at all points, namely $\Delta B/B \sim 10^{-4}$. This agreed the value of designed momentum resolution.

The field measurement technique was to pass a coil of wire through the magnetic field and measure the induced voltage, $E = -d\Phi/dt$, where Φ is the magnetic flux through the coil. The field was determined along the path by time integral of the voltage. Field calibration measurements were made with hall probes.

The induction coils used for field measurement was lent from a spectrometer and beam physics team of the NSCL. They adopted it to the mapping for the S800 spectrometer[3]. The coil consisted of very fine wire, whose diameter was 25 μm, spooled around a bobbin. The height of the bobbin was 12.7 mm, though the spool was only 9.53 mm tall. The wire was wrapped very tightly with a final diameter of 9.53 mm, a bore diameter of about 7 mm. The wires were copper, and given their diameter and resistance (about 6.7 k Ω, whose turns of the coil was about 30,000.) providing a large voltage signal. For example, the induced voltage

is ∼0.7 V at a field gradient of 60 mT/mm with moving velocity of the coil at 75 mm/sec. There were five of these coils, one on the magnetic medium plane, the others above.

The mapper was designed to be put on the surface of the pole or vacuum chamber of the two dipoles. The frame was 50 mm thick plate made of an alloy of aluminum, 2347 mm across, with the a central radius of 4400 mm to match the one of the dipoles. An angular extent was 28.73°. The arc lengths of the D1 and D2 were over 2.5 m and 4.6 m, respectively, and the mapper couldn't be made to cover whole the magnetic field of dipoles because it was quite difficult to keep the flat level of its surfaces. Then, we decided to prepare the mapper to measure just around the magnet fringes separately. The whole distribution would be reconstructed via analyzed the data.

The coils ride on a cart which was mainly compounded from fiber glass epoxy resin (G10) and its size was 800 mm × 300 mm including aluminum hardware attachment. It had four plastic guide rollers, two on each side of the guide, to enable the cart to roll back and forth on an arc of fixed radius. The cart was fixed in the vertical direction by eight wheels which gripped the side edge, which was parted from underside, of the plate. The cart was propelled on the guide rail by a stainless steel chain connected to a servo motor. The chain make a loop between a gear and a sprocket and fixed to the cart at its center.

A diagram for the measurement system is shown in Fig.1. The positions and times of the field measure-
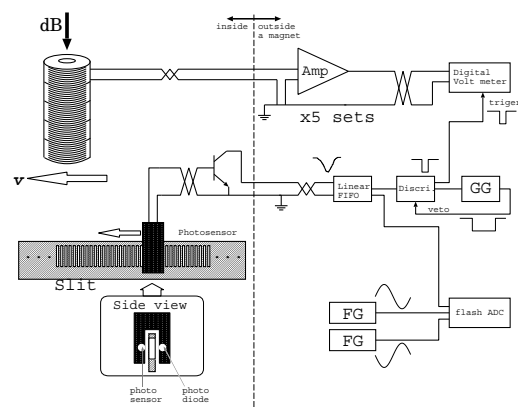
Fig. 1. Measurement system diagram

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ments were obtained by reading a small slit on a thin plate. The plate was put perpendicular on the top surface of the mapper. The size of each slit was 0.25 mm × 3.5 mm rectangular holes regularly spaced at a distance of 0.75 mm. A transmissive optical sensor, which contained a small infrared photodiode on one side of the slit plate, was used to detect the position of slit edge. The output of the transistor was supplied to the input of trigger for the data taking system. The timing of the output signals then translate into position information.

Simultaneously, the time intervals were deduced by a regular timing signals in every slit and accurate velocities were obtained. Fluctuations of output signals from the coils could be modified via the velocities at the every measurement point.

The production maps were taken at several current and field settings ranging from 0.15 to 1.5 Tesla for the D1 magnet and 0.17 to 1.66 Tesla for the D2, from 100 to 1000 Amps.

After the data correction, for example, off-set voltage at an amplifier output of each coil, cart velocity, coordinate and absolute magnetic field strength at the start and end point of the measurement, complete sets of the field distribution were obtained. The field distributions around magnet fringes forms not rectangular but continuous shape. From the analysis of the effective field boundaries (EFB) a substantial edge of the dipole magnets for the passing particles can be determined. From the entrance and exit points of the EFBs at the central rays in the dipoles, the effective field lengths (EFL) were also deduced at the excitation sets.

The relationship of the excitation current and the $B\rho$ was obtained for each magnet is shown in Fig. 2. By using these results, the experimenter can set the magnet field for particles with a certain $B\rho$ value.

Additionally, Fig. 3 describes the relationship between the EFL and the $B\rho$ values of a passing particle at the D1 and D2 magnets, respectively. A drastically shifts can be recognised over 6 Tm while the EFLs are constant within 0.1% below. The calculation of the beam transport can be referred the relationship of the $B\rho$ and the EFLs and one can describe the transfer matrices for an arbitrary situation.

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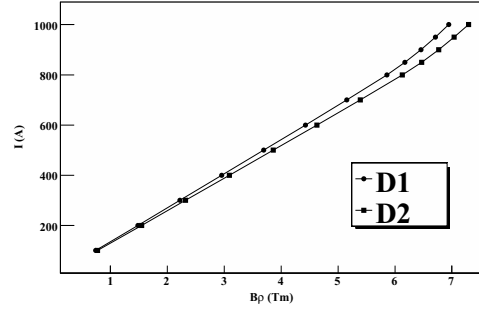
Fig. 2. The relationship of the excitation current and the $B\rho$ value at the D1 and D2 magnets.
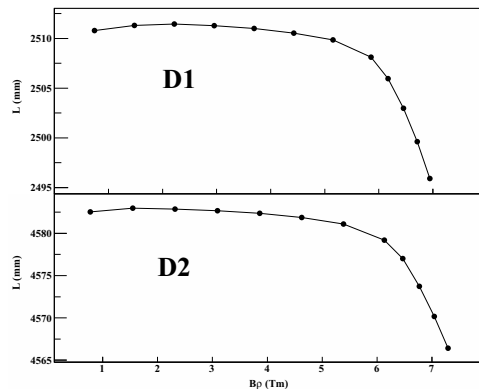
Fig. 3. The shifts of the effective field length (EFL) as a function of the $B\rho$ value at the D1 and D2 magnets.

Large acceptance transport in the high resolution beam line for SHARAQ spectrometer

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New missing mass spectroscopy with an RI beam is planned to be conducted at RIBF with the SHARAQ spectrometer[1]. The SHARAQ spectrometer is designed to achieve a resolving power of $p/\delta p = 1.5 \times 10^4$ and a high angular resolution of $\delta\theta \sim 1$ mrad for particles with a maximum magnetic rigidity of $B\rho = 6.8$ Tm.

To avoid loss of energy resolution due to the momentum spread of RI beams, the dispersion matching technique is applied to perform high resolution measurements[2]. The maximum resolving power 15000 is achieved in the dispersion matching (DM) mode. However, in the DM mode, a large target is needed because the image size at the target is about as large as 10 cm. High resolution achromatic (HA) mode is also prepared. In the HA mode, the beam size of the target is about a few cm with keeping the half resolving power of the DM mode if the beam trajectories are measured at F6. The resolving power and acceptance for the DM and HA mode are summarized in Table 1. Now the high resolution beam line is under construction based on the ion optical design[3]. In the commissioning run scheduled in March 2009, the measurements to determine the transfer matrix elements are planned.

Beam transports described above have the advantage of large resolving power at the cost of the small momentum acceptance of $\pm$ 0.3% as listed in Table 1. This is because the beam trajectories are spread out in accordance with the large dispersion of the beam line. In some experiments, more wider momentum acceptance transport mode is required for high intensity. The large acceptance (LA) achromatic mode is quite indispensable.

The beam trajectories of the LA mode obtained by the first order ion optical calculation using GIOS[4] are shown in Fig. 1. The transfer matrix obtained by the calculation is summarized in Table 2. In the calculation, strengths of quadrupole magnets by F5 are equivalent to the BigRIPS standard transport[5]. As shown in Fig.1, the beam is focused both horizontally and vertically at F6, FH7 and the Target, while the beam is focused only vertically at FH9. In this calculation, the momentum acceptance is limited by the beam size in STQ14, while the angular acceptance is limited by that in QH18.

The resolving power and acceptance are compared with other modes in Table 1. In the LA mode, mo-

mentum acceptance of $\pm$ 2% is achieved. On the other hand, the resolving power, which is the same value at F5 of BigRIPS standard is 1/10 of the DM mode. There is still some room for improvement in the LA transport. In the present calculation, polarities and locations of magnets are fixed to be the same as in the DM/HA mode. Due to the limitations, horizontal and vertical magnifications are not small enough in the LA mode. Investigation along these line is still in progress.

Transport mode	DM	HA	LA
Resolving power	15000	7500 (at F6)	1500 (at F5)
Momentum acceptance (%)	$\pm$ 0.3	$\pm$ 0.3	$\pm$ 2
Angular acceptance			
horizontal (mrad)	$\pm$ 10	$\pm$ 10	$\pm$ 20
vertical (mrad)	$\pm$ 30	$\pm$ 30	$\pm$ 20

Table 1. Resolving power and acceptance for high resolution beam line for SHARAQ. Transport mode of DM, HA, and LA indicate the dispersion matching mode, high resolution achromatic mode and large acceptance mode respectively.

$(x|x) =$	1.921	$(x|a) =$	0.000
$(a|x) =$	0.258	$(a|a) =$	0.520
$(x|\delta) =$	0.13		
$(y|y) =$	5.001	$(y|b) =$	0.002
$(b|y) =$	6.612	$(b|b) =$	0.225

Table 2. Transfer matrix elements of the large acceptance mode obtained from the first order calculation by GIOS[4]. The units for the lengths and angles are meters and radian.

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Target STQ19

FH9 QH18-a,b
QH17

QH16

FH8
STQ15

FH7
STQ14

STQ13
F6 STQ12

STQ11
F5 STQ10

STQ9
F4 STQ8

STQ7
F3 STQ6

STQ5
F2 STQ4

STQ3
F1 STQ2

F0 STQ1
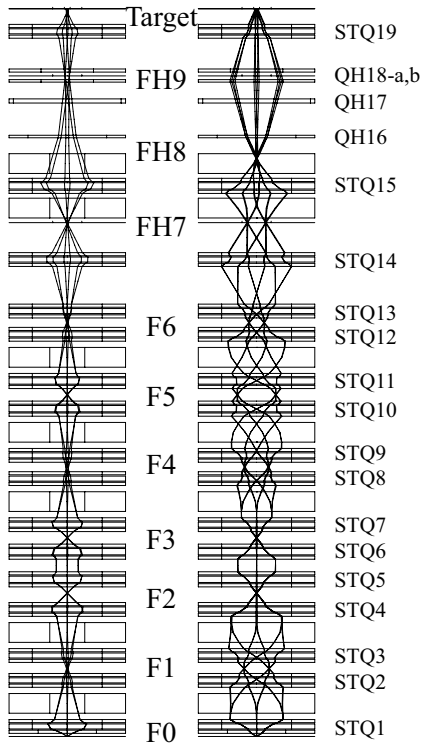
Fig. 1. Beam trajectories of the large acceptance mode
from F0 to the SHARAQ target. The left figure shows
the trajectories in the vertical plane, and the right one
shows that in the horizontal plane. The trajectories
with $x_0 = \pm 3$ mm, $y_0 = \pm 3$ mm, $\theta_0 = \pm 20$ and 0
mrad, $\phi_0 = \pm 20$ and 0 mrad, and $\delta_0 = \pm 2\%$ are also
drawn.

Development of low-pressure multi-wire drift chambers for BigRIPS and high-resolution beam line

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We are developing low-pressure multi-wire drift chambers (LP-MWDC's) that will be used at BigRIPS and the high-resolution beam line (HRBL) for experiments using the SHARAQ spectrometer.[1)] The SHARAQ spectrometer is designed to achieve a resolving power of $p/\delta p \sim 1.5 \times 10^4$ and an angular resolution better than 1 mrad for charged particles with maximum magnetic rigidity of 6.8 Tm. The high-resolution beam line is designed to fulfill dispersion-matching conditions when combined with the SHARAQ spectrometer. The simultaneous achievement of lateral dispersion matching and angular dispersion matching conditions is crucially important in using the SHARAQ

spectrometer for RI beams, which necessarily entail a large momentum spread. Details of the dispersion-matching beam transport are described in an other report.[2)] Figure 1 shows the BigRIPS, HRBL, and the SHARAQ spectrometer. The LP-MWDC's are used at F3, F6, F-H7, F-H9, and F-H10. Event-by-event tagging and tracking are needed at F3 for monitoring image size and at F-H10 to measure the momentum vector of the RI beam.

There are some requirements for the tracking detectors. The thickness of the detectors should be as small as $\sim 10^{-4}$ of the radiation length to reduce the effects of multiple scattering in the detectors to ~ 0.1 mrad. The efficiency should be as large as possible even for
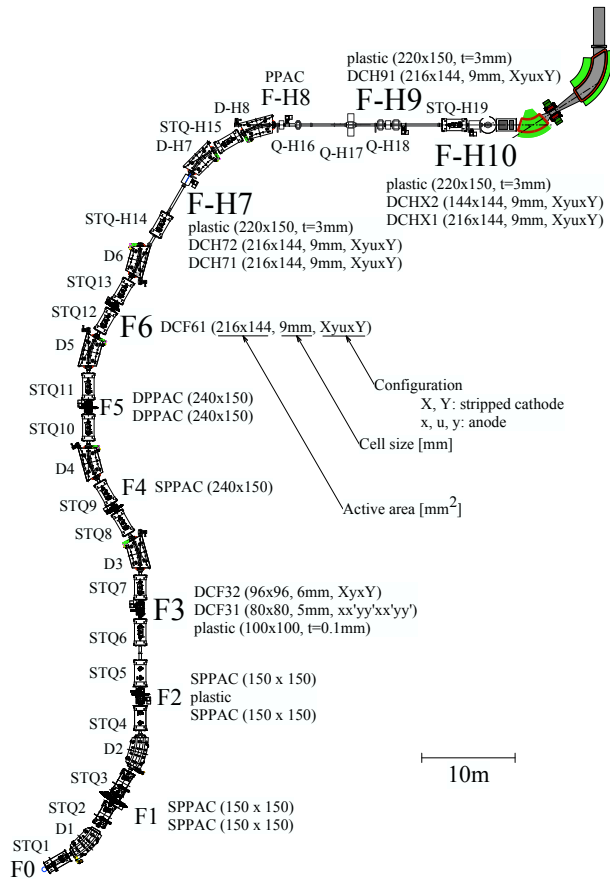
Fig. 1. LP-MWDC's in BigRIPS and high-resolution beam line.

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Table 1. List of LP-MWDC's in BigRIPS and HRBL.

Focal Plane	Name	Active area [mm²]	Cell size [mm]	Config- uration
F3	DCF31	80×80	5	xx'yy'xx'yy'
	DCF32	96×96	6	XyxY
F6	DCF61	216×144	9	XyuxY
F-H7	DCF71	216×144	9	XyuxY
	DCF72	216×144	9	XyuxY
F-H9	DCF91	216×144	9	XyuxY
F-H10	DCFX1	216×144	9	XyuxY
	DCFX1	144×144	9	XyuxY

X, Y: stripped cathode
x, u, y: anode
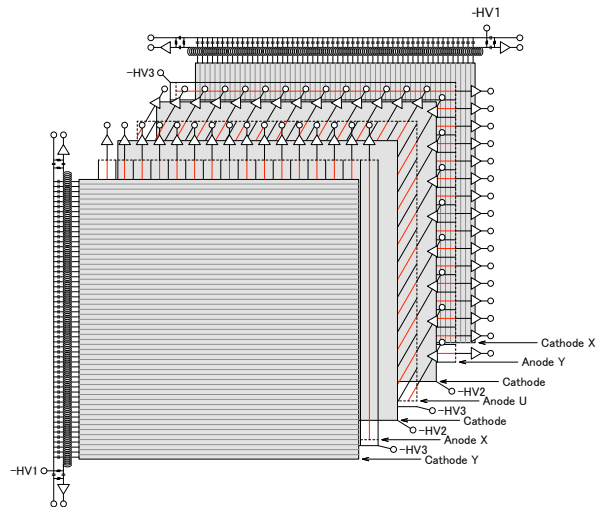
Fig. 2. Schematic view of DCHX2.

light RI beams such as ^{8}He at 200 MeV/nucleon. Position resolution is required to be less than 300 μm in FWHM. The maximum counting rate should be 1 MHz for the dispersive beam transport. Energy loss information should be obtained by the tracking detectors for particle identification of the RI beam to reject in-flight β-decay events.

The LP-MWDC's are being developed in order to realize the performance described above. Low-pressure operation at around 10 kPa is needed to reduce multiple scattering in the detector to as low as 0.1 mrad. The list of the LP-MWDC's is shown in Table 1. Details of DCF31 and DCF32 are described in other reports.[3,4] Figure 2 shows a schematic view of DCHX2. It includes three anode layers (x, u, and y) and two stripped cathodes (X and Y). The direction of the u wires is tilted by 30 deg. with respect to the x wires. The cathodes on the outside are stripped in vertical and horizontal directions (X and Y). The stripped cathodes give redundant position information, and the energy loss of the RI beam for particle identification. Signals from the stripped cathodes are read out using delay lines (DL's) which are used for the PPAC's.[5] Three high voltages can be supplied individually to the stripped cathodes, other cathodes, and the field wires. Signals from DL's are amplified by a Kaizu 3356 preamplifier. Signals from the anode wires are amplified and discriminated by REPIC RPA-130/131 64-ch. preamplifier and discriminator cards. The timing signals from RPA-130/131 are digitized by CAEN V1190A/B multi-hit TDC's.

We performed two experiments to evaluate the LP-MWDC's. Both experiments were carried out in the E7B course of RIBF operated by RIKEN Nishina Center and CNS, University of Tokyo. The beam was α at 8.8 MeV/nucleon which gives the same energy losses as ^{12}N at 200 MeV/nucleon, which will be used in the experiments using the SHARAQ spectrometer. Details

of the first experiment are described in other reports.[4] In the second experiment, we tested four LP-MWDC's, DCF31, DCHX2, DCHX1, and DCHX61. Figure 3 shows the experimental setup. The number of beams is counted by a 100-μm thick plastic scintillator located upstream of the LP-MWDC's. The vacuum of the beam line and the counter gas of the LP-MWDC's are separated by 50-μm thick aluminized mylar in front of DCF31. The configuration and the performance of DCF31 is described in another report.[3] DCHX2, DCHX1, and DCF61 have the same configurations described above. DCHX1 was set to the opposite direction, i.e. YxvyX, in order to have the same setup as F-H10. An aluminum plate with "SHARAQ" character is located downstream of LP-MWDC's backed by a 5-mm thick plastic scintillator. Data was collected for gas pressures of 4, 5, 10, and 20 kPa. Data analysis to evaluate efficiencies and tracking resolutions is now in progress.

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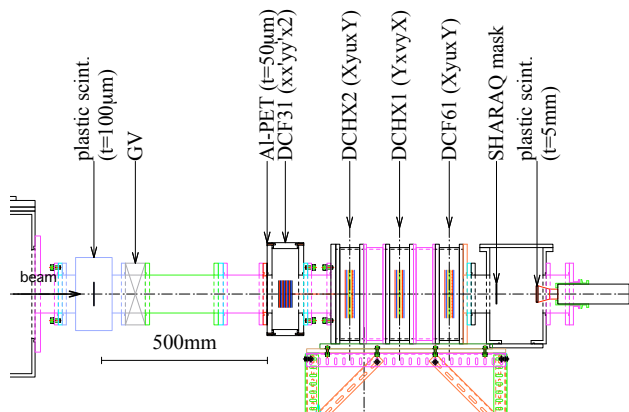
Fig. 3. Setup of the second experiment.

Development of Low-Pressure Multi-Wire Drift Chamber with Stripped Cathodes

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We are developing Low-Pressure Muliti-Wire Drift Chambers with stripped cathodes (LP-MWDCs)[1]. The LP–MWDC is used as a tracking detector in a high-resolution beam line[2] for experiments using the SHARAQ spectrometer[3]. The designed values such as the position resolution, efficiency and counting rate of the LP-MWDC are described in the previous report[1]. The LP–MWDC is designed for operation at a low pressure of counter gas to reduce the amount of materials. High efficiencies are required for light RI beam such as ^{12}N, ^{12}B, and ^{8}He at 100–300 MeV/nucleon.

Figure 1 shows a schematic view of the LP–MWDC with stripped cathodes. The LP–MWDC consists of 2 anode layers and 4 cathode layers. The outside cathode layers are stripped and connected with the delay line. The signals from the cathodes are read out through the delay lines which were developed for RIKEN PPAC[4]. The hit positions are determined both by the anode wires and stripped cathodes. Also, the position information of the cathode is used to resolve left-right ambiguity of the anodes. The counter gas is isobutane using as little as 20 kPa. The specifications are summarized in Table 1.

Table 1. Specification of the LP–MWDC with stripped cathodes

effective area	$96{\times}96$ mm^2
layer pattern	C_X-A_Y-C-C-A_X-C_Y
anode wire	20 μm$^\phi$, Au-W
potential wire	75 μm$^\phi$, Au-Cu
cell size	$6{\times}6$ mm^2
cathodes	Aluminized mylar, 1.5 μm^t
strip width and pitch	2.4 mm and 0.1 mm
counter gas	isobutane, 4–20 kPa
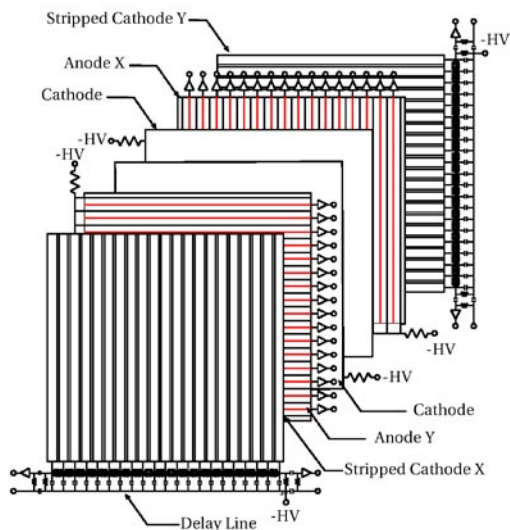
Fig. 1. Schematic view of the LP–MWDC with stripped cathodes

The LP–MWDC was tested for the α beam at 8.8 MeV/nucleon. The energy-loss of the α beam is com-

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parable to the ^{12}N beam at 200 MeV/nucleon. Here, we report results of a test experiment for checking the detection efficiencies, position extraction and energy-loss resolution involved in a simulation condition.

The experiment was performed with the beam at the E7B course at RIKEN RIBF operated by RIKEN Nishina Center and CNS, University of Tokyo. The α beam at 8.8 MeV/nucleon was supplied by the AVF Cyclotron. Figure 2 shows a schematic view of the experimental setup. A plastic scintillator, with the size of 5 mm^t and $50{\times}50$ mm^2, was placed at the downstream of the LP–MWDC as a trigger counter. The LP–MWDC was operated at the gas pressure between 4 kPa and 20 kPa. The timing signal of the anodes and cathodes and the pulse height of the cathodes were taken with a CAEN V1190A multi-hit TDC and a CAEN V792N QDC respectively.
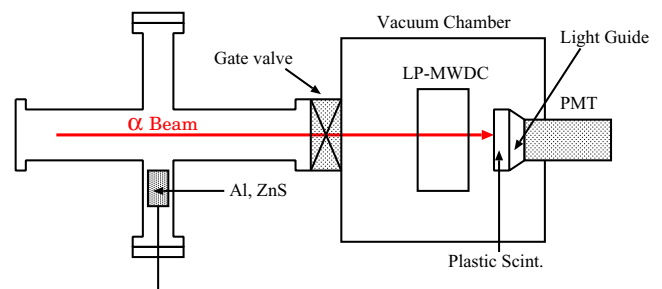
Fig. 2. Schematic view of the experimental setup

Figure 3 shows the detection efficiency of anode signals at a gas pressure of 20 kPa (open triangle), 15 kPa (closed square) 10 kPa (open square), 5 kPa (closed circle), and 4 kPa (open circle) as a function of the voltage applied to the cathodes and potential wires. The threshold levels of the anodes were evaluated to be 100 fC based on the energy loss of the α beam and the gas multiplication factor[5]. The efficiency of the

Fig. 3. The efficiencies of the anodes for gas pressures as a function of the applied voltage .

Fig. 5. Charge distribution of the cathodes.

anodes reaches up to $\sim 100\%$ at a low pressure in the range from 4 kPa to 20 kPa. The efficiency of the anodes satisfied the requirement.
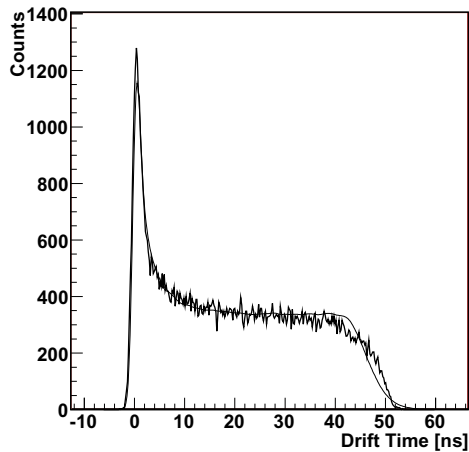
Fig. 4. Drift time distribution. The histogram is the distribution of the experimental data. The solid line is the distribution by folding the drift time obtained by means of Monte Carlo simulation.

Figure 4 shows the drift time distribution of the anode wire at 4.7 kPa and 850 V. The histogram is the experimental data, while the solid line is the distribution by folding the drift time distribution obtained by means of Monte Carlo simulation using the $GARFIELD$ code[5]. The distribution of the simulation is fitted to the experimental data. The function of space-time calibration is obtained with the simulation.

Figure 5 shows the charge distribution of the cathodes at 4.7 kPa. The energy-loss resolution evaluated from the data is found to be 40% in FWHM. The magnitude is compatible with an energy-loss difference for
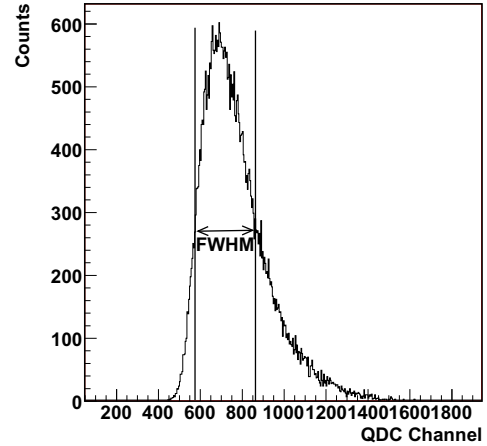
Carbon and Nitrogen with the same velocity. Energy-loss resolutions at 10 kPa and 20 kPa are 20% and 30 %, respectively. The LP–MWDC should be operated at a higher gas pressure to obtain higher energy-loss resolution for the discrimination of the particles.

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Performance evaluation of low-pressure multiwire drift chamber

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1 LP-MWDC - DCF31

Low-pressure multiwire drift chambers (LP-MWDCs) have been developed[1] as beam line detectors (BLDs) for the high-resolution measurement using the newly constructed spectrometer SHARAQ[2] in RIBF. One of the largest physical motivations of SHARAQ is to explore unknown regions in nuclear physics via the exothermic charge exchange reaction using radioactive isotope (RI) beams. For the high-resolution measurement with RI beams, the following requirements are imposed on the BLDs:

(1) position resolution better than 300 μm (FWHM) for the precise ray tracing.
(2) gas pressure as low as possible for sufficiently small energy struggling and multiple scattering effects.
(3) efficiency close to 100% for the event-by-event tracking.

The performances of LP-MWDCs were tested by using an accelerated beam[3]. In this article, we report on the performance evaluation for one of the LP-MWDCs, DCF31. DCF31 will be installed at BigRIPS-F3, which is the starting point of the high-resolution beam transport. The specifications and the schematic figure of DCF31 are shown in Table 1 and Fig. 1, respectively. Among the developed LP-MWDCs, DCF31 has the smallest cell size, 5×4.8 mm^2, and therefore it can work at a relatively high rate. This feature is favorable for the use at F3, where the beam spot size is a few millimeters.

Table 1. Specifications of DCF31.

Number of planes	8 (X$_1$X$_1$'Y$_1$Y$_1$'X$_2$X$_2$'Y$_2$Y$_2$')
Number of cells	16 cells/plane
Cell size	5 mm^w × 4.8 mm^t
Sensitive Area	80 mm × 80 mm
Anode wire	Au-W 12.5 μm
Potential wire	Cu-W 75 μm
Cathode foil	Al-PET 2 μm
Operation Gas	pure isobutane

2 Experiment

The experiment was performed at the E7 experimental hall in RIBF. The α beam was accelerated

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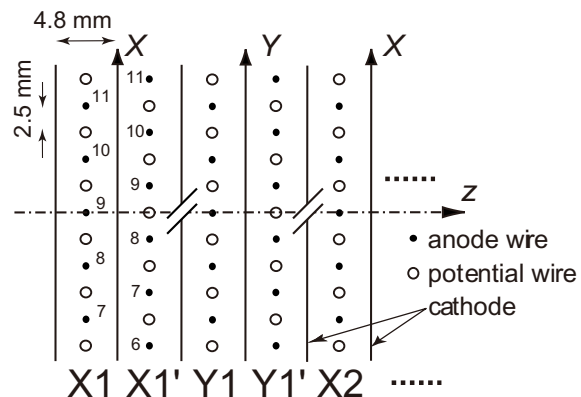
Fig. 1. The schematic view of DCF31.

up to 8.8 MeV/nucleon by the AVF Cyclotron and was transported to the E7B course. The α beam at 8.8 MeV/nucleon gives the same energy loss in DCF31 as the ^{12}N beam at 250 MeV/nucleon, which is a candidate for RI beam used in SHARAQ experiments. The transported α beam was defocused around DCF31 so that the beam covered a large part of the sensitive area. The signals from anode wires were amplified and discriminated by the REPIC RPA-131 cards. Since the typical noise level was about 5 mV, the threshold of RPA-131 was set to 10 mV throughout the measurement. The timing information was digitized by the CAEN V1190A multi-hit TDC. The plastic scintillator with a thickness of 0.1 mm was installed about 60-cm upstream of DCF31. The signals from the photo multiplier tubes triggered the data acquisition system.

One problem is that the number of crosstalks with the neighbor cells increases as the applied high voltage (HV) increases. This problem was solved by taking the timing information for both of the leading and trailing edges by V1190A. The pulse width of the analog signal can be obtained from $t_{trail} - t_{lead}$ as shown in Fig. 2. Since noise events have small pulse widths, they are clearly separated by gating on the pulse width as shown in Fig. 3.

3 Result

The obtained TDC spectrum is shown in Fig. 4. It has an ordinary shape which consists of a strong peak and a flat region. The width of the spectrum, corresponding to the drift time in a half-cell size, was about 40 nsec. This is consistent with the simulated value of 43 nsec by the program Garfield[4].

Figure 5 shows the efficiency curve obtained at gas

pressures of 5 kPa, 10 kPa and 20 kPa. The efficiency was estimated by $Y_{\text{X2}}/Y_{\text{trigger}}$, where Y_{X2} is the number of yields for X2 plane and Y_{trigger} is the number of triggered events. At 5 kPa, the applied HV tripped before the efficiency reached 100%. On the other hand, at 10 kPa and 20 kPa, it reached about 100% with the applied HV above 800 V and 900 V, respectively. Therefore the requirements (2) and (3) were met sufficiently.

The position resolution for each anode plane is estimated by the variance (residue) of the ray fitting. The overall position resolution for DCF31 is given using the half of it. The obtained resolution is shown in Fig. 6. The requirement (1) is satisfied above 8 kPa.

In summary, it was confirmed that the performance of DCF31 is satisfactory as a BLD at F3. DCF31 will be operated at a gas pressure of 10 kPa in the SHARAQ commissioning and in the subsequent experiments.

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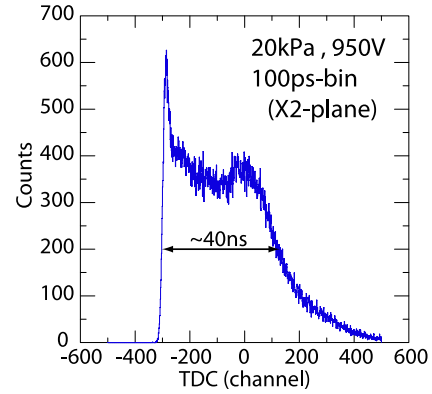
Fig. 4. Typical TDC spectrum obtained at 20 kPa and 950 V.
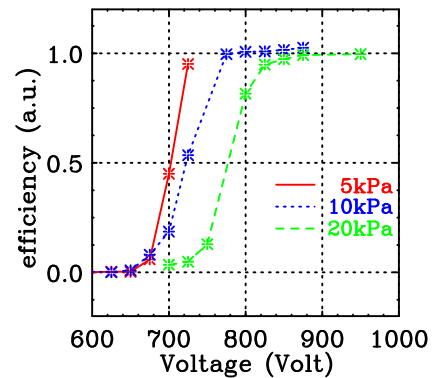
Fig. 5. Efficiency curve at 5 kPa, 10 kPa and 20 kPa. The efficiency is sufficiently high above 800 V (900 V) at 10 kPa (20 kPa), respectively.

Fig. 2. Pulse width of the anode signal obtained by V1190A. It is given by $t_{\text{trail}} - t_{\text{lead}}$.

Fig. 3. Event selection by gating on pulse widths. Noise events have small pulse widths and are clearly separated from true signals.
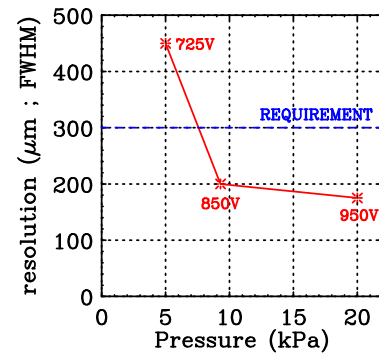
Fig. 6. Position resolution obtained for each of gas pressures. The requirement is satisfied above ~8 kPa.

Focal-Plane Detector for SHARAQ Spectrometer

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[SHARAQ spectrometer, cathode-readout drift chamber]

Constructions of the SHARAQ spectrometer[1] and the high-resolution beam line[2] are making progress in the RI Beam Factory (RIBF) at RIKEN. In order to realize high-resolution nuclear spectroscopy utilizing radioactive-ion probes, one of key devices is a tracking detector, located in the dispersive focal plane of SHARAQ, which is used to measure reaction Q values of induced reactions. Figure 1 shows a typical detector setup installed in the final focal plane of the SHARAQ spectrometer. The focal plane is located 3.04 m downstream from the exit of the SHARAQ-D2 magnet and is tilted at 35 degrees relative to the central orbit. The focal-plane detector system consists of a pair of tracking detectors, and a following plastic scintillator. The tracking detectors are used to measure the position and angle of particles and the plastic scintillator provides timing at the focal plane and energy deposit information. We have designed and manufactured the tracking detectors for SHARAQ by collaborating with an experimental group of GANIL.

The tracking detectors should fulfill the requirements necessary to successfully demonstrate the performance of the SHARAQ spectrometer, as summarized in Table 1. Eventually we adopted Cathode-Readout Drift Chambers (CRDCs)[3] operated at low gas pressure as appropriate tracking detectors. Although similar types of tracking detectors are used as focal-plane detectors in several magnetic spectrometers[4,5], we have to achieve smaller multiple scattering and higher position resolution.

Table 1. Requirements for the focal-plane detectors.

Effective area	> 500 mm (H)×300 mm (V)
Multiple scattering	≪ 1 mrad (σ)
Detection counting rate	> 10^3 particles/sec
Position resolution	300 μm (FWHM)
Detection efficiency	≈ 100%

Table 2. Specifications of the CRDC for SHARAQ.

Effective area	550 mm (H)×300 mm (V)
Anode wire (A)	10 wires, 20 μm$^\phi$
Potential wire (P)	11 wires, 75 μm$^\phi$
Frisch grid wire (F)	21 wires, 75 μm$^\phi$
Cathode pad (C)	2 mm (H) × 50 mm (T), 2 rows ×256 pads
Pitch of A-P and F-F	5 mm
Distance of A-C and A-F	3 mm
Mylar window	12 μm
Foil used for field cage	2.5 μm
Detector gas	Isobutane, 15–50 torr

Figure 2 shows the front view and cross section of the CRDC designed for the SHARAQ spectrometer, and its specifications are listed in Table. 2. The effective area of the CRDC is 550 mm horizontally and 300 mm vertically. The total thickness of the CRDC is 219 mm, and the depth of the sensor space is 104 mm. In the sensor part, 10 anode wires and 11 potential wires are alternately placed. The potential wires and Frisch grid are arranged to make axially-symmetric electric fields in the vicinity of anode wires and to minimize position dependence in avalanche gains. The two rows of the cathode pads are arranged horizontally in the vicinity

Fig. 1. Detector setup for the dispersive focal plane of SHARAQ.

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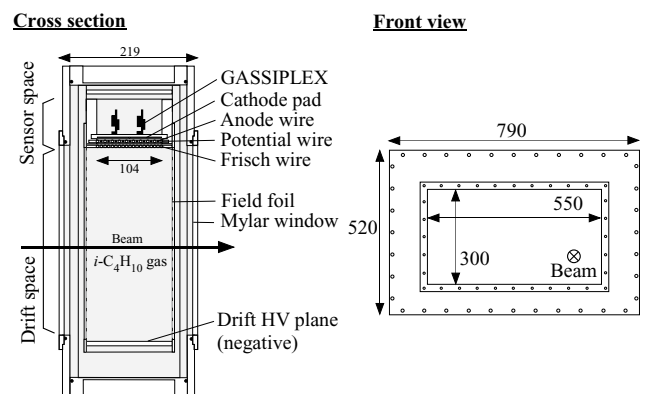
Fig. 2. Cross section and front view of SHARAQ CRDC. Front view is shown at half the scale of the cross section.

of the anode wires, and each row consists of 256 cath-
ode pads arranged with a 2.2 mm pitch. Negative high
voltage is applied in the drift space to form an electric
field for electron drift. The field cage is made up of
a drift high voltage (HV) plane and thin Mylar foils
on which gold strips are evaporated. A strip on the
Mylar foil is connected to the neighboring strips by re-
sistances, and a parallel and constant electric field is
provided by feeding voltage to the drift HV plane.

When a particle passes through the CRDC, sec-
ondary electrons produced by gas ionization move
along the electric field produced by the field cage, and
finally cause avalanches around the anode wires. The
vertical hit position is deduced by the drift time of sec-
ondary electrons and the horizontal hit position is de-
duced by the charge distribution induced on the cath-
ode pads. The maximum voltage for electron drift is
designed to be more than 5 kV. Under this condition,
the drift time for a 30 cm length in 15-torr isobutane
gas is estimated to be approximately 6 μs by using
the GARFIELD code[6]. The CRDC was designed for
use in vacuum and for operation at low pressures of 15–
50 torr. Low-pressure operation is effective not only for
reducing the thickness of gas itself but also for reduc-
ing the thickness of Mylar windows sealing the detector
gas. Multiple scattering at the CRDC is evaluated to
be approximately 0.1 mrad (σ) for ^{12}C at 200A MeV.

The CRDC outputs two signals of avalanches on the
anode wires and two multiplexed signals of charges in-
duced on the cathode pads. The charge induced on the
cathode pads is amplified, multiplexed and read out by
using the GASSIPLEX chips developed at CERN[7].
The GASSIPLEX chips are mounted close to cathode
pads inside the detector for noise reduction as shown
in Fig. 2. High-multiplexed performance allows us to
transmit charge signals from 256 cathode pads by us-
ing only one cable. The multiplexed signals are read
by a CAEN VME sequencer[8] and a CRAM module[9].
The readout process requires ~ 500 μs in total.

We have performed operation tests of the CRDCs
with 15 torr and 30 torr isobutane using an α source.
The triggers for data acquisition were produced by an-
ode signals from a CRDC itself. An induced charge
signal obtained from the cathode pads is shown in
Fig. 3. The histogram and curve are the obtained data
and a Gaussian fit result, respectively. Although the
Gaussian function, which is adopted in Ref.[5] as an
induced charge distribution, roughly reproduces our
data, further study on the shape of the charge distri-
bution is needed to measure particle positions more
precisely. We have also studied the spark limit and
avalanche gain of the anode wires. The CRDC oper-
ates stably with anode voltage as high as 1.0 kV al-
though all cathode signals are above that range. It is
reported in Ref.[10] that the avalanche gain of isobu-
tane increases by approximately 3 times as the anode
voltage increases by 100 V. Therefore, by considering
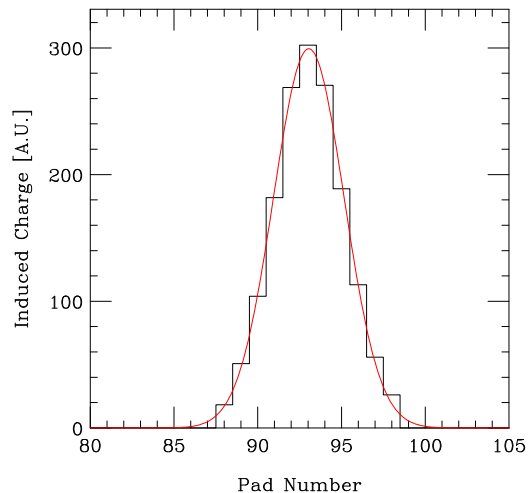
Fig. 3. An example of charge distribution data induced on
the cathode pads. The curve shows a Gaussian fit re-
sult.

energy losses by an alpha particle from the source and
an intermediate-energy heavy ion at CRDC, we esti-
mate that similar charge distributions are obtained by
the anode voltage of around 900 V for the case of 250A-
MeV ^{12}C particles.

In summary, we examined the setup configuration
of the focal plane detectors that utilize high-resolution
features of the SHARAQ spectrometer.

A large-area and low-pressure CRDC is adopted as a
tracking detector used in SHARAQ due to its good po-
sition resolution and reduced multiple scattering. The
CRDC operated well in 15 torr and 30 torr isobutane.
This detector system will be used in the commission-
ing of the high-resolution beam line and the SHARAQ
spectrometer in March, 2009.

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Gas-filled recoil ion separator GARIS-II

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[Gas-filled recoil ion separator, GARIS, superheavy, new element, hot fusion]

We designed a new gas-filled recoil ion separator GARIS-II. The construction of GARIS-II started in September 2008, and the spectrometer will be installed in the RIKEN linear accelerator (RILAC) facility in 2009.

1 Design concept

One of the world's most active gas-filled typed recoil separator GARIS[1] is operating at RIKEN. The separator has been used as a powerful tool for nuclear decay spectroscopy of superheavy element (SHE) nuclides produced via Pb/Bi-based fusion reactions (cold fusion), e.g., the search for a new 113th element using the ^{209}Bi(^{70}Zn,n)^{278}113 reaction.[2,3] Recently, GARIS has gained some experience in more asymmetric actinide-based reactions (hot fusion) with the aim of studying physical and chemical properties of SHE.[4] A gas-jet transport system coupled to GARIS as a pre-separator is a promising tool for next-generation SHE chemistry, i.e., identifying SHE nuclides under low background conditions with high efficiency of the gas-jet transport.[5] However, we also encountered some difficulties in these hot fusion studies. First, transmission in GAIRIS becomes much lower for actinide-based asymmetric reactions,[4] due to multiple scattering of the recoil ion by the filling gas atoms. Second, the background rate at the focal plane detector is 100∼1000 times higher than the cold fusion case. Third, GARIS cannot transport recoil ions with Z >110 produced via

Fig. 1. Schematic of new gas-filled recoil ion separator GARIS-II.

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^{248}Cm-based fusion reactions as considering an equilibrium charge state in a helium gas by our empirical data.[6]

GARIS-II was designed on the basis of extensive experiences with construction, development, and operation of GARIS. The most interesting subjects studied by GARIS-II are chemical investigations of elements with Z ≥104, nuclear reaction and nuclear structure studies of the SHE nuclides up to Z∼126 produced via actinide-based fusion reactions, and understanding the operating principles of gas-filled typed recoil separators such as the equilibrium charge state with various filling gases. Specifications and technical requirement for experiments performed by GARIS-II are:

- To irradiate actinide targets with high intensity beams of ^{18}O to ^{70}Zn over at least 2 pμA, and to operate GARIS-II under this beam condition.

  - To install a differential pumping system.
  - To install a rotating target system.
  - To install a beam dump made of Ta plate with a water cooling.
  - To install a movable and fixed slit to reduce the background due to the primary beam.

- To transport SHE nuclides produced via hot fusion reactions and achieve much higher transmission than GARIS.

  - To be able to transport recoil ions with magnetic rigidity $B\rho$ >2.16.
  - To have a larger solid angle than GARIS.
  - To be able to use various filling gases, such as He and He/H$_2$ mixture.
  - To be able to use both stable targets and actinide targets, such as ^{248}Cm, ^{238}U, and ^{232}Th with thick thickness of T >300μg/cm^2.
  - To have a short total path length < 5.76 m.

- To have high background suppression for unwanted projectiles and other by-products.
- To minimize the image size of the product at the focal plane.

2 Design and ion optical characteristics

GARIS-II consists of five magnets arranged in a Q_v-D-Q_h-Q_v-D configuration as shown in Figure 1. This configuration is the first design for the purpose of SHE study. The magnets are manufactured by Sumitomo Heavy Industries Ltd., according to specifications determined by RIKEN. Magnetic field model calcu-

lations were performed to optimize the basic design of dipole and the quadruple magnets using the simulation code OPERA.[7] The characteristics of dipole and quadrupole magnets are shown in Tables 1 and 2, respectively. Ion optical characteristics were analyzed using the computer code TRANSPORT.[8] The beam envelope in horizontal and vertical direction is shown in Figure 2 as a typical result for the case of the ^{248}Cm(^{22}Ne,5n)^{265}Sg reaction. Q1 provides strong vertically focusing and this focusing power better matches D1 acceptance. D1 separates the primary beam immediately, and mainly reduces the background at the focal plane of the system. An exit angle of 30 degree provides a little horizontal focusing. D1 is an H-type dipole magnet. The beam dump is designed to reduce the background due to the primary beam. Q2 and Q3 act as horizontal and vertical focusing to the focal plane of the system. D2 separates unwanted transfer products and light charged particles
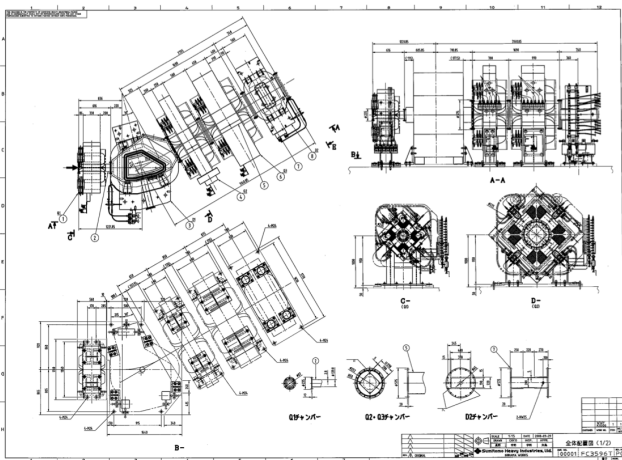
Table 3 provides a comparison between GARIS and GARIS-II in terms of the most important ion optical characteristics and its expected performance for typical hot fusion reactions of (A) ^{248}Cm(^{18}O,5n)^{261}Rf, (B) ^{248}Cm(^{22}Ne,5n)^{265}Sg, (C) ^{248}Cm(^{26}Mg,5n)^{269}Hs, and (D) ^{238}U(^{48}Ca,3n)^{283}112. Transmission was calculated while considering multiple scattering in target, angular spread by evaporation process, and multiple scattering in the filling gas. The solid angle is increased from 12.2 to 20.2 msr, approximately 1.7 times higher than GARIS. Therefore, transmission of GARIS-II is expected to be 2∼4 times higher than GARIS. The number of magnetic elements is increased from 4 to 5, and the total path length of the separator is decreased

Fig. 2. Beam envelope of ^{265}Sg ion calculated by TRANSPORT. Maximum horizontal and vertical angular acceptances are 48 and 118 mrad, respectively.

from 5.76 to 5.12 m. The separator vacuum chamber is filled with He (or He/H$_2$ mixture) from the the focal plane detector setup to the target region. The differential pumping system separates the helium filling from the high vacuum of the beam line. Continuous filling gas flow into the target chamber is regulated by a pressure/flow controller.

Table 3. Ion optical characteristics of GARIS-II and transmission anticipated for some types of hot fusions

	GARIS	GARIS-II
Configuration	DQ$_h$Q$_v$D	Q$_v$DQ$_h$Q$_v$D
Ang. acceptance (X) [mrad]	±61	±48
Ang. acceptance (Y) [mrad]	±57	±118
Solid angle [msr]	12.2	20.2
Total path length [m]	5.76	5.12
Maximum $B\rho$[Tm]	2.16	2.44
Possible SHE search [Z]	116	126
Dispersion [mm/%]	9.7	17.7
Transmission for reaction (A)	2%	8%
Transmission for reaction (B)	4%	16%
Transmission for reaction (C)	7%	28%
Transmission for reaction (D)	32%	75%

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Table 1. Characteristics of dipole magnets

	D1	D2
Deflecting angle [deg]	30	7
Maximum field [T]	1.74	0.86
Pole gap [mm]	150	200
Radius of central ray [mm]	1440	2850
Entrance angle [deg]	0	7
Exit angle [deg]	30	-7
Max. AT/pole [AT]	285600	146160
Number of turns/pole	476	336
Max. current [A]	600	435

Table 2. Characteristics of quadrupole magnets

	Q1	Q2	Q3
Max. field gradient [T/m]	12.2	4.70	5.27
Pole length [mm]	330	250	450
Bore radius [mm]	75	150	150
Max. AT/pole [AT]	37800	59070	59070
Number of turns/pole	108	179	179
Max. current [A]	330	330	330

Designing of ionization chamber for super-heavy elements

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In the field of super-heavy elements, the direct measurements of atomic number Z and mass number A of produced nucleus is a challenging task. One of the way to identify Z and A is to measure the energy loss per unit length dE/dx, and to measure total energy by stopping incident nucleus in a detector, respectively. A is derived from the combination of total energy and velocity of the nucleus. In the region of our interest ($Z > 100$, $A > 250$), the density of electron-hole pairs or primary electrons is too high in the semiconductor detector or even in a normal gas detector, because of large dE/dx. Too high density of electron-hole pairs provokes the recombination of electrons and holes. The number of electrons collected to electrodes comes to be unproportional to energy loss. As a result, the precise measurement of energy loss becomes almost impossible.

In this work, we make an attempt to operate the ionization chamber with low pressure to reduce the density of primary electrons. Our final aim is to measure the energy loss with a high degree of accuracy to identify Z and A of super-heavy elements.

Our detector is used for the nuclei with the total energy of several tens of MeV. Therefore, an amount of material other than gas filled in the effective area must be reduced as much as possible. For this purpose, anode and cathode electrodes are assembled parallel to the incident direction of nuclei. In addition, the anode electrode is segmented perpendicular to the incident direction of nuclei to measure dE/dx.

A prototype of the ionization chamber was previously constructed. As a result of operating tests using ^{241}Am and electric field computations using a Garfield code[1], a structural defect was found — a parallel electric field could not be formed in the effective area. In such a deformed electric field, analog signals obtained from each segment of anode electrode do not reflect the energy loss in corresponding segmented area because a part of electrons drift into a segment other than the segment in which the electrons are generated originally. Thus, it is impossible to measure dE/dx correctly using this prototype ionization chamber.

Consequently, we redesigned a new ionization chamber. The electric fields under various geometries and applied voltages we could envision are computed to achieve parallel electric field in the effective area using the Garfield code.

Figure 1 shows optimized geometry of the ionization chamber and voltages applied to each constituent.

Computed electric fields using the Garfield code under previous and optimized geometries are also shown.

The voltages applied to anode and cathode electrodes are 450 V and 100 V respectively. The effective area is held at higher potential than surrounding wall of ground. A ratio of applied voltages must be kept even if applied voltages are changed from the requirements such as detection efficiency or counting rate.

The field wires are arranged in three columns at both upstream and down stream of the effective area. The distance between wires is 2.5 mm. The distance between wire columns is 5 mm. The voltage between neighboring wires is 5 V. The voltages applied to wires in the outer two columns are higher than those in the inner one column by a 5 V. A difference in potential between surrounding ground and field wires causes deformed electric field, especially in the vicinity of anode electrode. By applying higher voltage to the outer columns, parallel electric field in the effective area could be achieved.

Two columns of wires are arranged on the lateral sides of the effective area. Similarly, the voltages applied to wires in outer column are higher than those in the inner column.

A new prototype of ionization chamber with the geometry described above has been constructed. The operating tests using ^{241}Am have just been started.
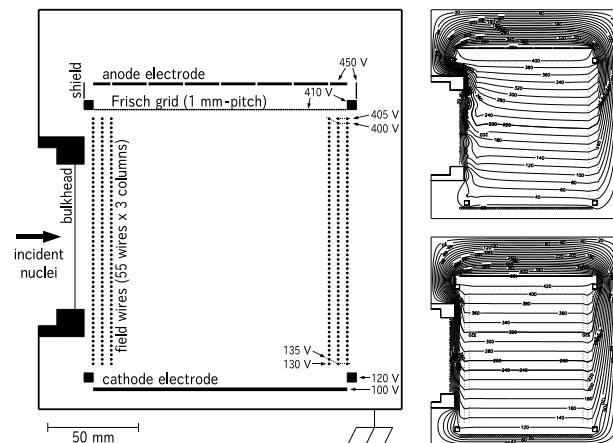
Fig. 1. Left: An optimized geometry of the ionization chamber and voltages applied to each constituent. Right: Computed electric fields under previous geometry (upper panel) and optimized geometry (lower panel).

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The Potential of a new LaBr$_3$(Ce) Based γ-Ray Spectrometer for Fast-Beam Experiments at the RIBF

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[Gamma-ray detection, high resolution scintillators]

Gamma-ray spectroscopy at intermediate and relativistic beam energies for present state-of-the-art spectrometers is hampered by either an energy resolution of only about 10 % if scintillation detectors are employed or by a very low full energy peak (FEP) efficiency for Ge-based arrays. For the former, the intrinsic energy resolution is the limiting factor, while Ge has an excellent energy resolution, but is a very expensive material. Thus, a Ge-based spectrometer covering the entire solid angle to obtain a high FEP efficiency would be extremely costly, in particular since pulse shaping algorithms have to be applied that keep the Doppler-broadening due to the detectors' opening angles small.

The new scintillation material LaBr$_3$(Ce) possesses energy resolutions of 2 and 3 % (FWHM) at $E_\gamma = 1333$ and 662 keV[1], respectively, unprecedented for scintillators. Due to its highly reduced price per volume compared to Ge material and the high γ-ray absorption coefficient, LaBr$_3$(Ce) is an excellent choice to build a 4π γ-ray spectrometer. This array is suited especially well for in-beam γ-ray spectroscopy if crystal geometries are chosen that minimize the Doppler broadening. To study the potential of a LaBr$_3$(Ce) based spectrometer for the recently commissioned Radioactive Isotope Beam Factory (RIBF), simulations with the GEANT4 package are performed.

The aims for the complete array are set to an energy resolution of 3 % (FWHM) and a FEP efficiency of 40 % for 1 MeV γ-rays emitted at 100 MeV/u. The geometry of all single crystals is chosen to have an identical boxed-shape to ensure a high amount of flexibility for changes in the configuration of the complete array. The crystals are arranged in rings of the same polar angle in such a way that the opening angle induced Doppler broadening is kept constant for all detectors.
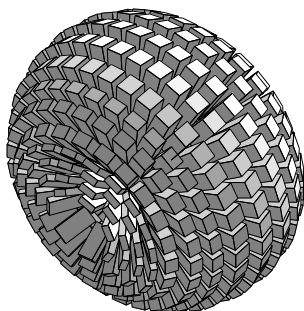
To reduce the Al housing material, part of the crystals are put into common housings of two and three crystals, respectively.

Taking these restrictions into account, different detector geometries have been investigated. Fig. 1 shows the configuration for crystal sizes of $15 \times 40 \times 80$ mm^3 and a total of 915 detectors. For this configuration, the simulated energy resolution and FEP efficiency for 1 MeV γ-rays emitted at 100 MeV/u are 3.1 % and 38 %, respectively, including the reconstruction of the total energy for add-back events.

These values have to be compared with present γ-ray detection arrays as DALI2[2] and RISING[3]. The DALI2 array was simulated in the configuration with 182 NaI(Tl) detectors, while for RISING the 15 Ge Cluster and 8 Ge Miniball detectors were taken into account. The comparison of the three arrays is given in Tab. 1. The gain of energy resolution is about a factor three compared to DALI2, while the FEP efficiency is higher. Compared to RISING, the energy resolution is about at the same level, while the gain in FEP efficiency is more than a factor six. A high efficiency is extremely important to pin down new level schemes with multiple decays from γ-γ coincidences. Here, the advantage for two coincident 1 MeV γ-ray decays detected is about a factor 40 over RISING, demonstrating the high potential of a new LaBr$_3$(Ce) based γ-ray detection array.

Table 1. Comparison of simulated energy Resolutions and FEP efficiencies ϵ_{FEP} for 1 MeV γ-rays emitted at 100 MeV/u of the γ-ray detection arrays DALI2, RISING, and the LaBr$_3$(Ce) based array. ϵ_{FEP}^2 corresponds to two 1 MeV γ-rays with both FEPs being detected.

Array	Energy resolution [%]	ϵ_{FEP} [%]	ϵ_{FEP}^2 [%]
DALI2	8.4	30	9
RISING	2.5	6	0.36
LaBr$_3$(Ce)	3.1	38	14

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Fig. 1. Schematic Layout of LaBr$_3$(Ce) array.

Beta-counting systems for decay-spectroscopy projects[†]

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[Nuclear structure, unstable nuclei, beta-decay]

Beta-decay studies are unique and powerful probes of nuclear structure. The high sensitivity of beta counting systems is essential, especially to approach nuclei farthest from stability with extremely low production rates. We have developed two types of beta-counting systems to extract decay properties of rare-isotopes such as half-lives, level-schemes, and Q_β dedicated for fast beam experiments. The preparation status of decay spectroscopy projects will be reported.

1 DSSSD

A high resolution beta-counting system consisting of six double-sided silicon strip detectors (DSSSD : Micron Model W1-1000) has been developed. This system is designed for high efficiency beta-gamma spectroscopy. The position correlation of the implanted ions and associated decay beta-rays enables us to deduce the decay curves without pulsing the beam. Simultaneous measurements of heavy-ions and beta-rays require an extremely wide dynamic range of readout electronics. Thus, we have developed low noise readout electronics with the dynamic range from 20 keV to 4 GeV[2]. In addition, a freezer system was introduced to cool the DSSSD down to -25 degree to minimize the threshold energies as well as to reduce radiation damage in the DSSSD. The performance of the DSSSD system was tested using heavy-ion beams as reported in Reference[3]. This system can be used for high efficiency gamma-ray measurements associated with beta-decay and isomeric decay by incorporating Ge detectors. Five Clover type Ge detectors can be placed surrounding the DSSSD in close geometry. Three independent automatic refilling systems of liquid nitrogen have been developed for stable operation of the Ge-detector array.

2 CAITEN

Decay spectroscopy of rare-isotopes at a high counting rate of beams is challenging for a high statistics decay spectroscopy experiment. We have developed a novel system (CAITEN) comprised of two primary subsystems. One is a large cylindrical plastic scintilla-tor (TPS: ϕ500mm x1000mm, 20mm^t) as an active implantation target. The other is a twenty-four position-sensitive photomultiplier-tube (PSPMT: Hamamatsu H8500) array arranged inside the TPS[1]. The TPS consisting of 4×10^4 pixel scintillators (5x5x20mm^3) is designed to be rotated to measure the half-lives of many isotopes simultaneously. The positions of beta-rays are reconstructed by measuring the pulse height differences of the PSPMT's anode lines with a registive-chain. Figure 1 shows the correlation between the position of beta source ^{90}Sr and the reconstructed position from the PSPMT with a rotation speed of TPS at 60 rpm. We confirmed an adequate position resolution of $\sigma \sim 4$mm after position calibration.

Reconstruction of decay curves for isotopes in a cocktail beam environment requires event matching of implanted ions with associated decays. We have developed new analysis frame (r2pro.cxx: Rawdata-To-Paw-ROot), which provides the platforms for CERN-LIB (cfortran)[4] and ROOT[5] users. Online monitoring will also be implemented in the code in oder to have a consistent analysis frame.

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4) URL: http://cernlib.web.cern.ch/cernlib
5) URL: http://root.cern.ch
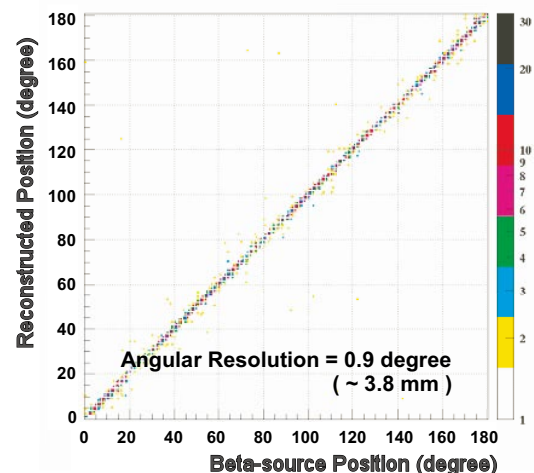
Fig. 1. Correlation between location of beta-source and reconstructed position using PSPMTs.

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Beam test of double-sided silicon-strip detector for decay spectroscopy

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Decay spectroscopy is one of the most powerful tool to study an exotic structure of unstable nuclei. Unstable nuclei with several hundreds MeV/nucleon provided by the BigRIPS are stopped in an active stopper at the end of the beam line. β and γ rays emitted from stopped nuclei are detected by double-sided silicon strip detectors (DSSDs) as the active stopper, of which thickness is 1 mm, and Clover-type Ge detectors surrounding the stopper, respectively.

A total energy of implanted nuclei is measured for particle identification by DSSD, and its β decay is detected by the same DSSD. The energy loss of a β ray is very small compared with the energy loss at implantation of unstable nuclei. The typical energy loss for β ray with several MeV is 300 keV in 1mm-thick silicon. The length passing through and also the energy loss in the DSSD changes as a function of the implantation depth and the emission direction of β ray. So the energy loss ranges down to 0 keV.

A new readout system of DSSD has been developed, which has a wide dynamic range from 20 keV to 4 GeV [1]. The signal was divided into the two pre-amplifiers with low and high gains for several-GeV and down to 20 keV energy-loss detection, respectively. And we need to make a position correlation between the implantation and the emitted β ray in order to know the parent nucleus of β decay under the condition of a continuous and cocktail beam. Here, we report the test of this readout system using stable beam of ^{132}Xe at HIMAC and unstable beam of ^{18}N at CNS Radio Isotope Beam separator[2] (CRIB).

The energy deposit in the DSSD with 1 mm thick is 4 GeV at a maximum for neutron-rich nuclei around ^{110}Zr. In order to test the measurement of such a large energy deposit with DSSD, we have performed an experiment using a ^{132}Xe beam with 400 MeV/nucleon at HIMAC. Since the ^{132}Xe beam passed through the DSSD, not the total energy but the energy loss ΔE in the DSSD was measured. Three kinds of ΔE between 2 - 3 GeV were measured, where ΔE was changed by degrading the beam energy using adjustable aluminum energy degraders. Figure 1 shows the ΔE spectrum of 2.03 GeV and Fig. 2 shows the energy scale using $\Delta E = 2.03, 2.18$ and 2.83 GeV. The measured scale was linear, but the extrapolation of the line to the
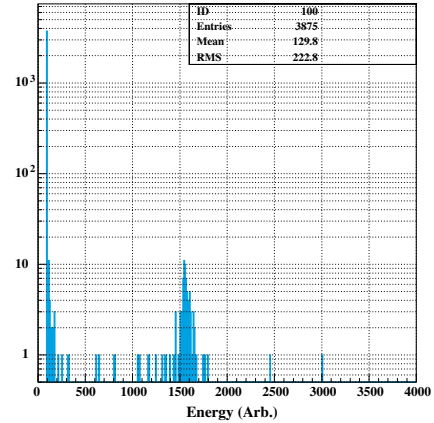
Fig. 1. Energy loss of ^{132}Xe beam in the Si detector. Horizontal scale is arbitrary unit. Peak position corresponds to 2.03 GeV.
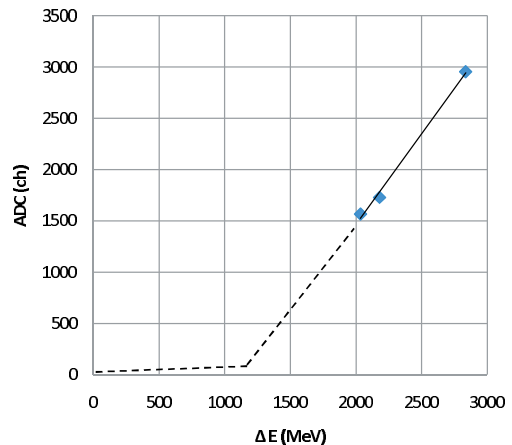
Fig. 2. Energy scale using three kinds of energy loss of ^{132}Xe. Dashed line shows an extrapolation based on response for pulser.

lower energy deviated from the zero channel. This deviation was consistent with the result using a pulser as written in the previous report[1]. When a signal is beyond a saturation of the high-gain preamplifier, the ratio of charge division changes and the energy scale of the readout system including the low-gain preamplifier is bended. The energy resolution was about 1.5 % as shown in Tab. 1. The resolution was not good due to the saturation of the high-gain preamplifier. This res-

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olution is, however, good enough to identify a charge state of an in-flight particle with $Z = 40$.

Table 1. Energy resolution in FWHM as a function of energy loss, ΔE, in the DSSD.

ΔE (GeV)	FWHM (%)
2.03	1.7±0.4
2.18	1.5±0.5
2.83	1.1±0.3

We have tested the β-ray detection and the position correlation by using the unstable beam. ^{18}N ($T_{1/2} = 624$ ms) beam was produced through the reaction, ^{9}Be(^{18}O, ^{18}N)^{9}B and separated by CRIB, and the energy implanted in DSSD was 50 MeV. The total production rate was 14 cps and the purity of the ^{18}N beam was 14%. Main contaminant was ^{17}N ($T_{1/2} = 4.17$ s) and its purity was 56%. Two 1mm-thick DSSDs were placed at F2 of CRIB. The ^{18}N was implanted in the first DSSD. The implantation position was determined from a strip which have largest signal among strips. The strips of the second DSSD was connected together because this DSSD was used for the coincidence about β ray.

The ^{18}N was implanted near the surface, therfore the β ray emitted to the direction of the surface was not detected. On the other hand, the β ray emitted to another surface was detected, of which a minimum energy loss was 300 keV. The energy-loss spectrum of β ray in DSSD was shown in Fig. 3. The coincidence spectrum with another DSSD was shown as the dashed line. The noise less than 200 ch and the energy loss of 300 keV around 400 ch were clearly separated. While the noise level at F2 of CRIB was higher than 20 keV, the lower noise level is expected at the BigRIPS beam line because the 20 keV was achieved at a cave around the BigRIPS in the previous test[1]. The time spectrum of β decay under the position correlation between the implantation and the decay events was shown in Fig. 4. The half life was determined to be 560 ± 70 ms, which was consistent with the known value 624 ms[3]. The decay event of ^{18}N was extracted purely against β-unstable contaminants.

In summary, we tested the DSSD with the newly developed readout system using the stable beam of ^{132}Xe at HIMAC and the unstable beam of ^{18}N at CRIB. The signal of 2 - 3 GeV energy loss of ^{132}Xe beam was measured. The linearity and the resolution were checked. The β ray from ^{18}N was measured by the DSSD where ^{18}N was implanted. The decay event was extracted by the position correlation between the implantation and the β ray. The performance satisfied the requirement of the decay spectroscopy.

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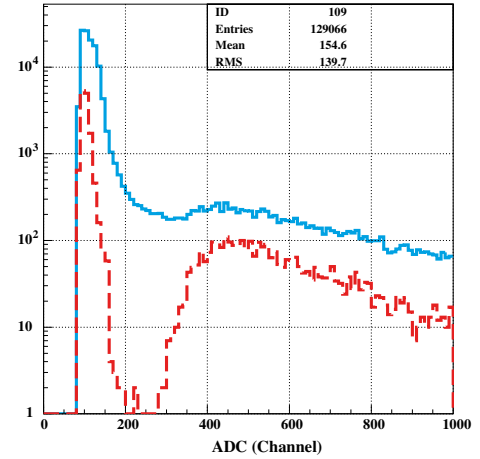
Fig. 3. Energy loss of β ray in the first DSSD. The dased line shows the coincidence spectrum with the second DSSD. 400 ch was about 300 keV.
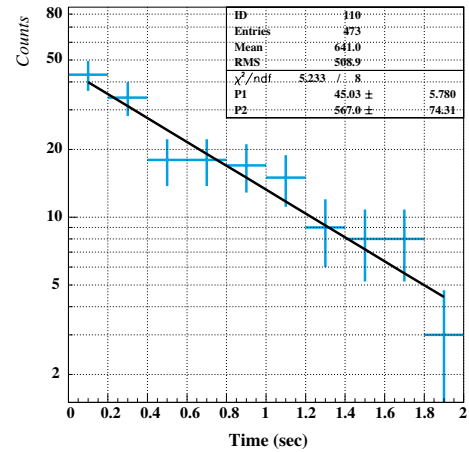
Fig. 4. Time spectrum from the implantation of ^{18}N to the β-ray detection with the position correlation between the implantation and the β ray. The line shows the best fit of decay curve with no background component.

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Development of thick solid hydrogen target

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We have developed a thick solid hydrogen target (SHT)[1,2] to use for reaction cross-section measurements of unstable nuclei. Until now, a liquid hydrogen target (LHT) was used in the measurements at RIKEN [3]. SHT has some advantages compared to LHT. (1) In SHT, distension of entrance and exit windows is less than that in LHT, and that allows us to make a target with a large area; thinner entrance and exit windows are also available with SHT. (2) In SHT, temperature control is not necessary. (3) Density of SHT is larger than that of LHT.

Figure 1 shows a schematic view of a target cell of SHT. The cell is made of a copper block, which allow us to make SHT with $\phi 50$ mm diameter and 100 mm length. Thickness of this SHT corresponds to about 0.9 g/cm^2. Beam windows of SHT were made of kapton foils with 25μm thickness. To cool the target cell we used a cryocooler refrigerator, which has a cooling power of 1.5W at 4.2K. Hydrogen gas is put into the cell through an SUS tube, as shown in Fig. 1.

Figure 2 shows a schematic view of the vacuum chamber for SHT and the system to supply hydrogen gas. The SHT cell is surrounded by the thermal-radiation shield in the vacuum chamber ($\sim 10^{-6}$ Torr). The thermal radiation shield made of copper shields the SHT cell from external heat. The cryocooler connected to the He compressor was used to cool the SHT cell. It takes 4 hours to reach about 5K. Only the necessary amount of hydrogen gas is supplied into the H2 tank since the gas is flammable. Hydrogen gas was supplied into the SHT cell at a constant pressure (100 Torr) by a control valve. After starting the supply of gas to the SHT cell, it takes 150 minutes to complete

Fig. 2. Schematic view of system to supply hydrogen gas.

the SHT. Figure 3 shows a picture of a typical completed SHT. Dark shadows on the top of the figure are cracks which were produced just after completion of the SHT. If the gas pressure is high, more cracks are produced. On the other hand, if the gas pressure is low, hydrogen gas remains in the SHT as bubbles. The system is maintained at a constant optimal pressure of 100 Torr to minimize cracks and bubbles. The SHT can be melted by a heater, located at the top of the cell, and it returns to the H2 tank (see Fig. 2) gas. At the beginning of this recovery process, we also use a silicon rubber heater, which wraps the recovery tube in order to melt solid hydrogen inside the tube. Total time for recovery is about 30 minutes.

The present SHT system was installed at F11 of the zero degree spectrometer for Day-one experiment in December 2008. We checked homogeneity of SHT by using the secondary beam and measured the charge changing cross-section for some light neutron-rich nuclei. Analysis of the results is now in progress.

Fig. 1. Schematic view of SHT cell.

Fig. 3. Appearance of typical SHT.

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Parasitic production of slow RI-beam from a projectile fragment separator by ion guide Laser Ion Source (PALIS)

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A new heavy ion accelerator facility and a projectile fragment separator, BigRIPS[1] provide a wide variety of short-lived radioactive isotope (RI) ions without restrictions on their lifetime or chemical properties. The beams are however, not adequate for precision atomic spectroscopy. We therefore proposed a universal slow RI-beam (SLOWRI) facility as one of principal facilities of RIBF using a gas catcher cell with an RF-carpet ion guide[2]. The R&D work for SLOWRI is successfully progressing and some spectroscopy experiments on Be ions have been performed[3,4]. Beam time at such a modern accelerator facility, however, is always limited and operational costs are often high. We therefore propose an additional new method to drastically enhance the usability of such an expensive facility. At RIBF, a single primary beam produces thousands of isotopes simultaneously but only one isotope is used for an experiment while the other >99.99% of isotopes are simply thrown away. We propose a new method to collect such dead isotopes for a slow RI-beam by installing a laser ionization gas catcher in the vicinity of the first or second focal points of the fragment separator BigRIPS, which will provide parasitic RI-beams free of operational cost.

The fragment separator, BigRIPS, consists of a pair of magnetic separators with an energy degrader placed in between. A single isotope beam is, in principle, obtained by the two-stage separation. All contaminant ions with slightly different A/Z are stopped in the slit at the focal point of the first separator (F1) and dozens of isotopes in the vicinity of the desired isotope are stopped in the slit at the second focal point (F2). Our aim is to collect those isotopes lost in the slits. Due to space and accessibility constraints, a big gas cell like the one used in SLOWRI is not possible, so we must use a compact cell with a simpler mechanism. The proposed setup is shown in Fig. 1. We will place one or more compact gas cells on the side of the main beam path. Each gas cell will be filled with 1 bar Ar gas whereby most injected ions can be neutralized. A degrader located in front of the cell will adjust the beam energy to efficiently stop the ions inside the

cell. The neutralized atoms will be transported by gas flow toward the exit of the cell, where the atoms can be re-ionized by laser radiations. This uses the same principle as the conventional IGISOL[5] for the transport and LISOL[6] for the re-ionization scheme.

Although the size of the cell is limited, the high-pressure Ar will enable efficient stopping of energetic RI-beams. In order to ionize the neutralized RI-atoms efficiently, a multi-step resonance ionization method will be used with high power and high repetition rate pulsed lasers. Resonance ionization within a gas cell has been studied intensively at the Leuven[6], Mainz[7], and Jyvaskyla[8] groups. The re-ionized RI ions from the gas cell will be transported by SPIG[9] through multiple differential pumping stages to an electro-magnetic mass separator. Although the new method is not as universal as the original SLOWRI, the purity of ions can be extremely high. Separations by A/Z are made at BigRIPS, by Z via laser ionization, and by A at the mass separator. Fig. 2 shows one example of a part of available laser-ionized isotopes in an in-flight fission from ^{238}U beam aiming for ^{125}Pd, when the gas cell is placed X=75 mm at the F1 slit. This intensity means the number of RI ions entering into the entrance of the gas cell whose diameter is 50 mm. The result may imply an adequate yield for even post acceleration.

One of the important issues in the gas catcher system is the extraction time to avoid the decay loss of short-lived isotopes. The proposed gas cell solely uses

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*7 Department of Physics, Texas A&M University
*8 Department of Physics, K.U. Leuven

Fig. 1. Schematic image of the laser ionization gas catcher setup.

The number of incoming particle into the gas cell
ions/sec (for primary beam 1p μ A)
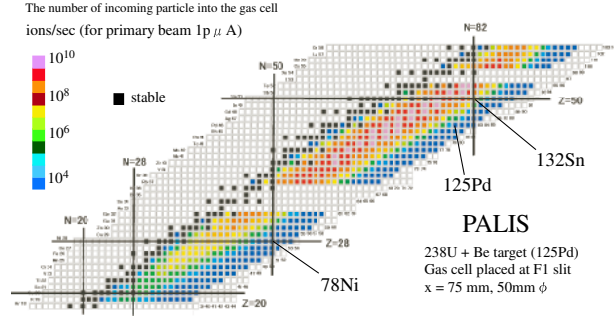
Fig. 2. A part of available laser-ionized isotopes in an in-flight fission from ^{238}U beam aiming for ^{125}Pd, when the gas cell is placed X=75 mm at the F1 slit (the cell entrance is 50 mmϕ).

gas flow to guide stopped nuclei towards the exit hole of the cell. This extraction time is therefore determined by the volume of the cell and the conductance of the exit hole. The accessibility for short-lived nuclides was evaluated by using a flow calculation and a macroscopic simulation including diffusion loss. The evaluated total efficiency shown in Fig. 3 is obtained from a product of the total survival efficiency against decaying, the stopping efficiency and an assumed additional efficiency factor. This additional factor consists of the laser ionization efficiency and other possible loss, such as molecular formation and beam transport to SLOWRI. Based on experimental results at Leuven for Ni isotopes[12], this additional efficiency factor was evaluated to be 10%. The evaluated total efficiency suggests that more than 1% overall efficiency is still expected for nuclei with a half-life of longer than 1 s. The practical yield obtained by PALIS is a product of this total efficiency and the intensity shown in Fig. 2.
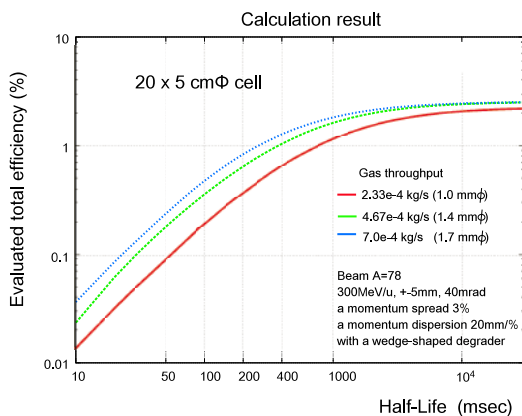
Fig. 3. Evaluated total efficiency of PALIS as a function of the half-life of the nucleus for different gas throughput.

Historically some distinct phenomena have been observed in the various gas catcher systems. The most serious problem is that the extraction efficiency from the cell diminishes with increasing rates of incoming particles[10,11]. This phenomenon can be explained as an effect of space charge in the cell. During the process of stopping in the gas cell, one incoming ion produces more than 10^5 ion-electron pairs and the electrons are removed quickly by the applied dc field, while the buffer gas ions remain in the cell for a longer period of time. The buffer gas ions distort the external field which is applied to transport the thermal ions towards the exit. The distorted electric field causes losses in the transport of RI-ions. The equilibrium space-charge density is proportional to the square-root of the beam intensity and the transport efficiency is roughly proportional to the reciprocal of the charge density[11]. In the proposed scheme, however, the RI-ions are intentionally neutralized and transported exclusively by the gas flow. The effect of the space-charge must be minimal. A drastic efficiency enhancement for the high-intensity beam was observed using a laser ionization gas cell at LISOL Leuven[12] (Fig. 4). A high efficiency is still preserved with 10^{10} pps beam of ^{58}Ni.
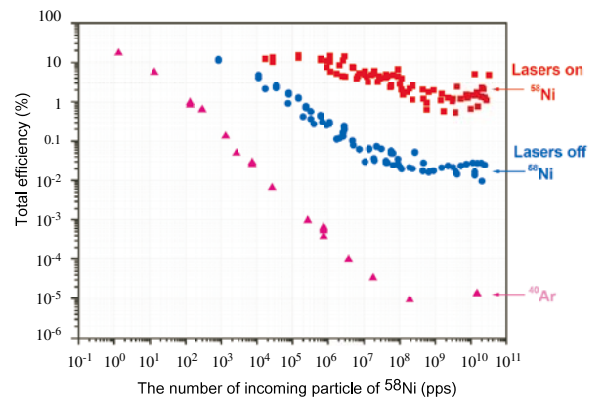
Fig. 4. Experimentally measured total efficiency of the laser ionization gas cell for ^{58}Ni at Leuven[12].

We have presented a new experimental method to provide parasitic slow RI-beams from a projectile fragment separator without disturbing the primary RI-beam experiment. This is an additional option for RIKEN universal slow RI-beam facility, SLOWRI.

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A Portable Multi-Reflection Time-of-Flight Mass Spectrograph for SLOWRI[†]

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[Mass measurements, unstable nuclei, low energy beam]

We are continuing the development of a multi-reflection time-of-flight (MRTOF) mass spectrometer for use with radioactive ion (RI) beams. The MRTOF will be attached to its own dedicated gas stopping cell, allowing the system-as-designed to be portable. This will provide flexibility in commissioning the device by making it possible to use less-demanded RI sources, such as CRIB, while still being easily moved to other RI-beam sources at RIKEN – or even being relocated to another facility.
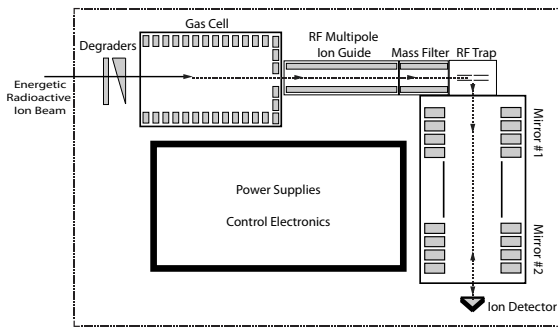
Fig. 1. Planned layout for the portable MRTOF system. The system includes a gas cell for stopping relativistic ions, an ion trap to prepare ions for injection into the MRTOF and ion guide systems for transporting thermalized ions from the gas cell to the ion trap. The hatched box indicates that the entire system is portable.

Figure 1 provides a sketch of the system. Energetic ions will be slowed in a solid degrader and thermalized in a helium-filled chamber. Thermalized ions are injected into a radio-frequency (RF) multipole ion beam guide to be transported through a differentially pumped region after being extracted from the gas cell using a proven RF-carpet technique[1]. An RF quadrupole mass filter will select for a specific ion mass number, removing non-isobaric ions. The isobaric ion ensemble will then be cooled in a low-pressure gas-filled RF ion trap before being injected into the MRTOF.

An early off-line prototype previously achieved a mass resolving power of $R \approx 2 \times 10^5$, with a measurement time of $t \approx 7$ ms for A/q=28 ions[2)3)]. However the efficiency at such a resolving power, while never quantified, was low. The on-line system, still under de-

velopment, is expected to be able to achieve even better resolving powers with a high efficiency. Efficiency improvement will result from reducing the emittance of ion pulse extracted from the trap and improving the vacuum level in the flight chamber; enhanced resolving power will result from achieving extremely high-stability voltage supplies for the MRTOF electrodes and reducing the energy and time spreads of ion pulses extracted from the ion trap.

To study the most exotic isotopes, the entire system must be highly efficient. To minimize space charge effects, a cryogenically cooled gas cell will be used. This will reduce gas impurities which might charge exchange with ionized helium. While the RF-carpet technique does not transport He$^+$, gas impurities ionized by exchange with helium ions can lead to a powerful source of impurity ions which can reduce extraction efficiency from the system due to space charge effects.
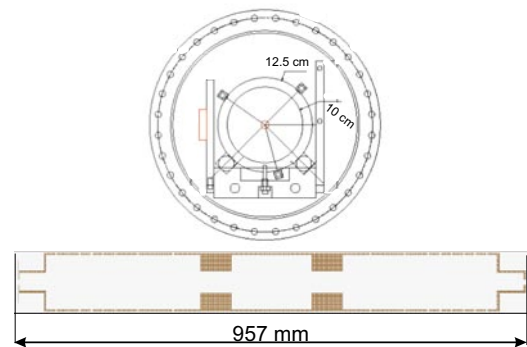
Fig. 2. (top) Mechanical drawing of MRTOF mounting, showing vacuum chamber, C-shaped mounting bracket, ceramic mounting rods and ring electrode. (bottom) Sketch showing electrodes for MRTOF.

As the total flight length may be as much as 1 km, the emittance strongly effects the the efficiency of the system. The energy spread of the ions directly effects of the maximum resolving power of the system. To address these issues, the ion trap will also be cryogenically cooled, which should lead to a reduction in the energy spread and emittance of the cooled ion cloud.

Figure 2 shows the mechanical layout of the MRTOF system. The system will be mounted on a heavy base of Titanium, with side-panels to minimize sagging effects. Titanium has been chosen because it has a low coefficient of expansion (9 ppm/K) which is well-matched the the coefficient of expansion for the ceramic insula-

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tors which will be used. This should help to minimize systematic effects from changes in the flight length. Additionally, Titanium has better vacuum properties while being much less magnetic than stainless steel.

A new ion trap of novel geometry is being developed for the MRTOF-MS. The trap uses a pair of printed circuit boards, each consisting of three strip electrodes. An RF signal applied to the outer electrodes creates a confining quadrupole pseudo-potential. The strips are segmented to allow an axial potential well for ion trapping. The ions are introduced into the trap parallel to the electrodes; after cooling, the ions are ejected perpendicular to the trap through a small ($r = 100$ μm) hole in the central electrode. This geometry should produce very well-cooled ions without affecting the MRTOF-MS vacuum, leading to highly efficient operation. Figure 3 shows a photo of one of the printed circuit boards used to build the ion trap.
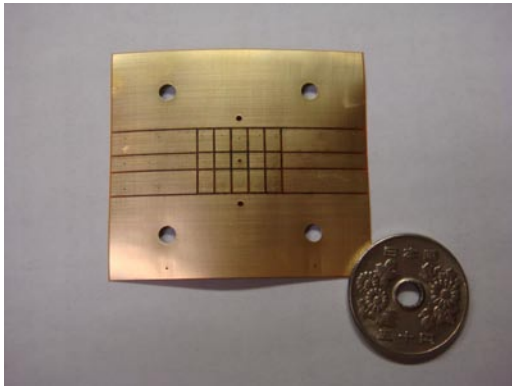
Fig. 3. Photograph of one of the printed circuit boards used to construct the ion trap. A ¥50 coin is shown for scale.

To optimize the voltage distribution and determine the maximum mass resolution which we can expect, a large number of simulations have been performed. These calculations have recently been reported[4]. For minimally cooled ion clouds ($R_0 = 100$ μm, $T = 3000$ K), calculations indicate that a mass resolving power of $R_m \approx 5 \times 10^5$ can be achieved, as shown in Fig. 4. With such resolving powers it would be possible to resolve most long-lived isomeric states, making the device highly competitive with Penning trap mass spectrometry (PTMS). Furthermore, the fast measurement may allow the MRTOF-MS to exceed PTMS for sufficiently short-lived isotopes, as indicated in Fig. 5.

Development work for the portable MRTOF-MS is ongoing. The MRTOF electrodes and vacuum chamber have been sent for fabrication and are scheduled to arrive near the end of FY2008. The vacuum chamber and mounting for testing the new ion trap system has been sent for fabrication and is scheduled to arrive in February, 2009. At present, it is foreseen that construction of the system should be completed early in FY2009 with commissioning to begin thereafter.
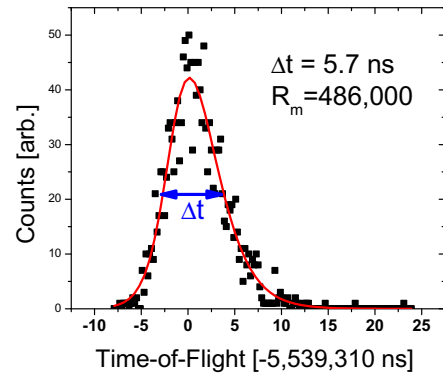
Fig. 4. Calculated time-of-flight pulse for $A/q = 28$ ions after 518 laps in the MRTOF-MS, assuming a minimally cooled ion cloud ($R_0 = 100$ μm, $T = 3000$ K) with an rise time of $t_r = 1$ μs for the MRTOF injection electrode. The full-width at 1% for this ion pulse represents Δm $\approx \pm 75$ keV – indicating that the MRTOF-MS may be able to resolve *isomers*.
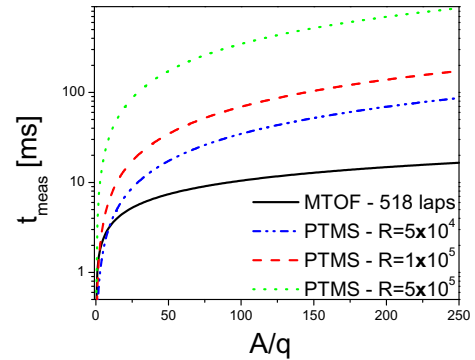
Fig. 5. Comparison of MRTOF and a 9.4T PTMS in terms of measurement time as a function of atomic mass. The resolving power for the MRTOF depends on many factors, however $R = 5 \times 10^4$ should be easily achievable with 518 laps. Thus, it is clear that the MRTOF will require much shorter measurement times than PTMS.

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Development of an absolute laser frequency counting system

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Precision spectroscopy of atomic transitions is almost the exclusive method used to determine the nuclear charge radii of unstable nuclei. In such measurements, narrow-line-width continuous-wave lasers are often used and the wavelengths or frequencies of the laser radiations must be accurately known. Fortunately, nowadays a clockwork optical femtosecond frequency comb[1)] can provide an exact "scale" for laser frequency measurements. A common method to provide a laser radiation with an accurate frequency and a high stability is to "lock" the user's laser frequency to the frequency comb. However, this method is not always applicable. For example, in our laser-laser double resonance spectroscopy experiments[2)], we need to use two scannable laser radiations. Also in our collinear laser spectroscopy with parallel-antiparallel configuration[3)], two laser radiations should be scanned simultaneously and independently. Although, it is possible to scan the frequency of a laser radiation locked to a frequency comb by scanning the repetition rate of the femtosecond laser, the scanning rate is slow and we need to have two frequency combs for two independent laser radiations. A frequency shifter based on an acousto-optic modulator can provide scanning capability from a fixed frequency laser, however the usability of such a device, especially for UV radiation, is limited.

We therefore used two commercial dye lasers with their own scanning and stabilization functions (using attached reference cavities) and *measure* the laser frequencies from the beat frequencies resulting from interference with a frequency comb. The dye laser frequency f_{dye} can be obtained using

$$f_{\mathrm{dye}} = nf_{\mathrm{rep}} \pm f_{\mathrm{offset}} \pm f_{\mathrm{beat}}, \tag{1}$$

where f_{rep} is the repetition rate of the femtosecond laser which is flexible around 250 MHz, f_{offset} is the offset frequency of the frequency comb which is usually fixed to 40 MHz, and f_{beat} is the beat frequency between the comb radiation and the dye laser radiation. The integer n and the polarity of f_{offset} can be obtained from other calibration sources, such as an wave meter and an iodine molecule cell. The polarity of f_{beat}, on the other hand, can be obtained from the trend of the beat frequency itself.

We have developed a system for counting the beat frequencies of dye laser radiations, which may fluctuate or jitter during measurements. It consists of a beat signal detection setup for two laser radiations, a filter circuit for counting the beat frequencies and software to reconstruct a spectrum as a function of the true laser
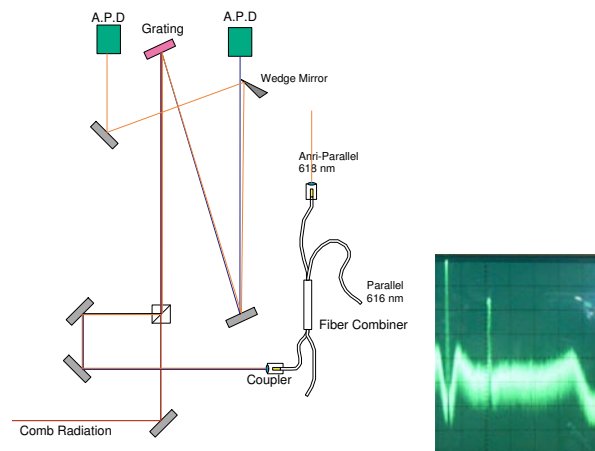
Fig. 1. Layout of the interaction region of the frequency comb radiation and the dye laser radiations (left) and beat signal of a dye laser observed in a spectrum analyzer scope. The left peak is a reference signal of the spectrum analyzer and the right peak is a beat signal.

frequency. Figure 1 (left) shows a schematic diagram of the detection scheme for two laser radiations in the case of collinear spectroscopy experiments. Two laser radiations were merged in a fiber combiner and interact with the comb radiation. Since the wavelengths of the two lasers are slightly different for the parallel and antiparallel beams, the interfered signals can be separated by a grating mirror and detected in two independent avalanched photo diodes, allowing the beat frequencies to be counted simultaneously. In the case of laser-laser double resonance spectroscopy for Be isotope ions, however the frequency difference between the two 626 nm radiations is too small to be separated by a grating. We saw two beat frequencies mixed in a spectrum analyzer scope, or we chopped the radiations and measure them alternately.

A typical beat signal observed in a spectrum analyzer is shown in Fig. 1 (right). It is often contaminated by higher harmonics and spurious signals. A filter circuit with many band-pass filters was used to eliminate such noise signals and count the true beat signal (Fig. 2). The circuit consists of amplifiers made of current-feedback operational amplifier devices AD8002, band-pass filter modules from Mini-Circuits, discriminators made of fast comparator devices MAX962, and pre-scalers made of AC393 or MC12026. The beat signals from all filter channels and fluorescence signals were counted simultaneously in a multi-input multi-channel scaler device made of PCI6607 interface cards. A short time interval of

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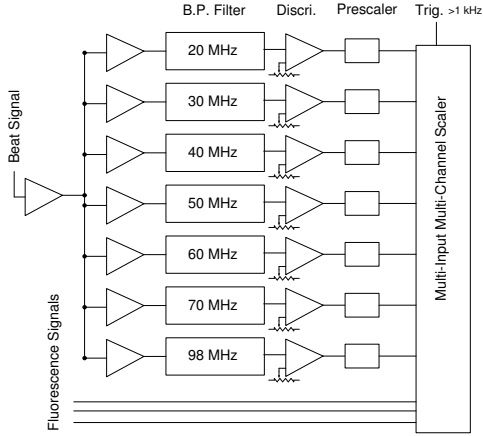
Fig. 2. Block diagram of the filter circuit for beat frequency counting.
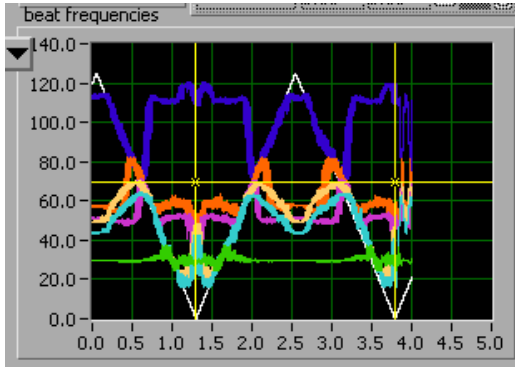
Fig. 3. Beat frequencies measured through multiple band pass filters during a laser scan
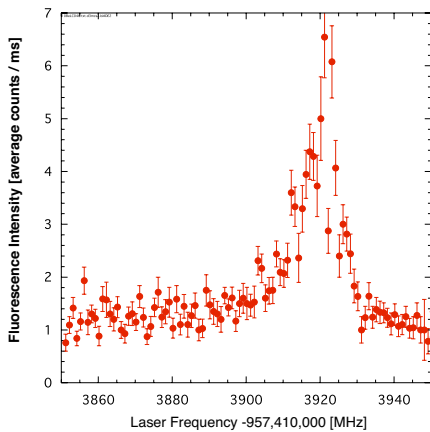
Fig. 4. Laser cooling spectrum of $^{10}\text{Be}^+$ ions plotted as a function of the absolute laser frequency.

$t_{\text{bin}} < 1$ ms was used to track the relatively fast jittering of the dye laser frequency.

Figure 3 shows plots of the beat signal counts as a function of the scanning time. The observable range of the beat frequency covered as wide as from 15 MHz to 110 MHz while the vicinity of the turning points, 0 MHz and 125 MHz, are always suffered from the spurious signals. When the count values were not in the range of the band-pass filter, the beat frequencies are spuriously reported. This can be corrected for through the use of defined range table for each filter along with partial range overlap between the neighboring band-pass filters and correlation with the scan time.

Only with these consistency checks, can the absolute laser frequency be obtained through determination of the n-value, the polarity of f_{offset}, and the true beat frequency during each t_{bin}. This value can be stored along with the counts of the fluorescence signals detected during the time bin.

The number of the fluorescence count per t_{bin} may be small since a typical counting rate of the fluorescence signal is several kcps. We need to sum several time bins to show a spectrum. If one sums the spectrum according to the succeeding time bin, which is equivalent to measuring with a longer t_{bin} as used in ordinary laser spectroscopy, the effects of fluctuations and jitter become significant. To remove the effects of fluctuations and jitter, we should sum the spectrum according to the *measured* laser frequency which is tagged with the fluorescence count data for each time tin. In this *frequency-binning* process, however, the number of the measurements which belong to the same frequency bin is not constant. We defined the intensity in units of counts per t_{bin} as an average of the count number for all measurements which belong to the frequency bin while the statistical uncertainty is obtained from the total fluorescence counts in the frequency bin. In this way, we achieved a true frequency spectrum as shown in Fig. 4 even though the laser frequencies were not stable. It should be noted that such a method allows us to sum up multiple scans even if the laser scanning is not reproducible.

The frequency counting system has been used for precision spectroscopy of optical transition frequencies of $^{7,9,10,11}\text{Be}^+$ ions. Development is in progress to achieve better performance. So far we use commercial counter interface cards for the multi-input multi-channel scaler, however we plan to use an FPGA based hand-made multiple counter interface to increase the number of input channels and the flexibility of the system.

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Development of fluorescence detection system for nuclear laser spectroscopy in He II

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We are developing a fluorescence detection system for nuclear laser spectroscopy of RI atoms stopped in superfluid helium (He II). This project is called OROCHI (Optical RI-atom observation in condensed Helium as Ion-catcher) and aims to perform laser spectroscopy of unstable nuclei even with a production yield of 10 pps.[1]

Detection efficiency must be maximized while minimizing background count rates in order to observe laser-induced fluorescence (LIF) from the low yield of unstable nuclei. Detection efficiency is maximized by using a Fresnel lens in close geometry with a cryostat. The Fresnel lens has a large diameter and short focal length. This introduces a large solid angle for collection of LIF. The background, which mainly originates from the excitation laser, can be reduced by using a wavelength filter, because the wavelength of fluorescence is sufficiently separated from that of excitation in He II.[2] In this project, the fluorescence detection system is used not only to observe fluorescence from unstable nuclei, but also to detect emission light from a plastic scintillator, which is placed in the cryostat and used for adjusting the stop position of RI beam in He II.

Figure 1 shows the configuration of the fluorescence detection system. It consists of three Fresnel lenses, a spatial filter (SF), a wavelength filter, and a photomultiplier tube (PMT). The light emitted from atoms is collected and focused on the SF by the first Fresnel lens (FL1). The SF is used to reduce stray light. Light which has passed through the SF is collimated with the second lens (FL2) so that the light enters at normal incidence to the wavelength filter for perfect separation of wavelength. The light is then focused on the photoelectric surface of the PMT by the third lens (FL3).

To optimize the configuration of the system, we performed an optical simulation for the wavelengths 793 nm for LIF of Rb atoms and 425 nm for emission light from the plastic scintillator. The highest light collection efficiency was found to be 6.8% for 793 nm and 5.1% for 425 nm, by calculating with various focal lengths and positions of lenses. It should be noted that light transmission efficiency for each lens was assumed to be 100% in the calculation.

A fluorescence detection system for 425 nm was built based on the simulation. The focal lengths of the lenses are 45 mm, 20 mm, and 70 mm for FL1, FL2, and FL3, respectively. All the optical elements are mounted in a black box. The position of lenses can be adjusted along three axes using micrometers. The spatial filter consists of two slits placed along the x and y axes of a surface perpendicular to the optical axis. The position and width of the slits can be tuned using micrometers. The detection system is mounted just below the cryostat. The light transmission rates for FL1, FL2, and FL3 have been measured using a laser and are 29.7%, 90.7%, and 89.7%, respectively. The transmission rate for FL1 is relatively low because FL1 is used to focus diverging light, even though the Fresnel lens used is designed to focus parallel light to a single point. The total light collecting efficiency of the system is estimated to be 1.2% based on the simulation and the transmission rate measured using the laser light.

In the beginning of January 2009, a test experiment on the fluorescence detection system was carried out in the E7 room of the RIKEN Accelerator Research Facility. In this experiment, a ^{2}H beam of 9.1 MeV/u was passed through two aluminum rotatable degraders used to lower the beam energy and a plastic scintillator used to count the number of ^{2}H particles. The ^{2}H was then injected into a cryostat and stopped in another plastic scintillator placed on the optical axis of the detection system. The emitted light from the scintillator was collected and detected by the detection system. Analysis of the data is in progress.
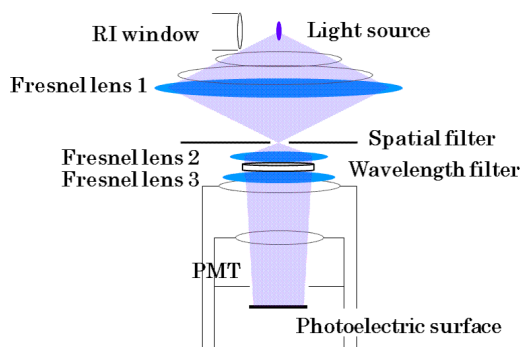
Fig. 1. Fluorescence detection system.

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[*4] Department of Physics, Osaka University
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Production of polarized Ag atoms by optical pumping in superfluid helium

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Polarized nuclei/atoms are one of most powerful tools for investigating nuclear properties, precise atomic structures, and fundamental physics. More specifically, our plan is to investigate nuclear electromagnetic properties such as nuclear spins and moments by measuring the atomic hyperfine or Zeeman structure of polarized atoms with laser-microwave/radiowave double resonance spectroscopy.

The optical pumping method is the most effective technique for producing high polarization of atoms, although the number of elements that can be optically pumped and polarized is limited. By using the optical pumping technique under superfluid helium conditions, we have achieved a large atomic polarization in Ag atoms for the first time. In this report, we describe details about optical pumping in superfluid helium.

The experimental setup is shown schematically in Fig.1. At the beginning of measurement, Ag atoms are laser-sputtered from an Ag metal sample disc placed approximately 1 cm above the helium surface, and are then introduced into the optical detection region in He II.[1] Next, the introduced Ag atoms are optically pumped and polarized by irradiation with circularly polarized pumping laser light tuned to the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ line of Ag atoms in He II.[2] The circular polarization of pumping laser light is generated using a $\lambda/4$ wave plate. In optical pumping, we apply a static magnetic field ($\simeq 7$ Gauss) to hold the atomic polarization generated by optical pumping.
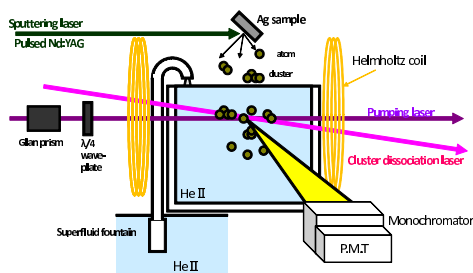
Fig. 1. Schematics of experimental setup

The polarization of optically pumped atoms is deduced from the measured laser-induced fluorescence (LIF) intensity of atoms with switching on and off the static magnetic field. It is to be noted that the LIF intensity I observed with irradiation by pumping light is related to the polarization of Ag atoms as

$$I \propto N_{\mathrm{atom}} \times (1 - P_l \times P_z), \qquad (1)$$

where N_{atom} is the number of Ag atoms, P_l is the circular polarization of pumping laser light, and P_z is the electronic spin polarization of the atoms.[3] Then LIF intensity is decreased gradually by increasing the polarization of atoms in optical pumping. From comparison of LIF intensity with and without the static magnetic field, the maximum polarization of Ag atoms in optical pumping is deduced to be more than 60%. The imperfection of achieved polarization is mainly due to the incomplete polarization of pumping laser light (70-80 %) because the wave plate we use is not suited for the wavelength of laser light. The atoms might be polarized much more if we used a wave plate suitable for the pumping laser wavelength.

Using the optically pumped Ag atoms, we have also measured the Zeeman splitting energy of the Ag atoms in He II using the laser-rf double resonance.[3] Figure 2 shows the Zeeman resonance spectrum of stable ^{107,109}Ag atoms in He II. We can deduce the nuclear spin of ^{107,109}Ag from the peak position of the resonance spectrum[3] as shown in the inset of Fig.2. Applying this optical pumping technique and double resonance technique to our project for nuclear laser spectroscopy in He II (named OROCHI), we can also measure the electromagnetic properties (nuclear spin, moment, and so on) of exotic Ag isotopes near the dripline region which can not be measured with traditional methods.
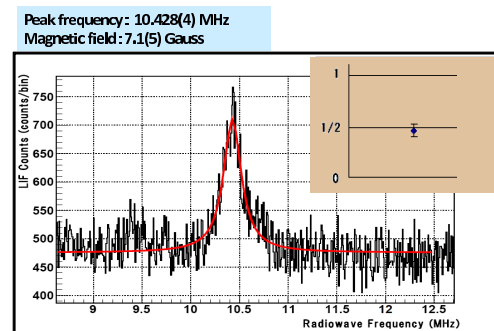
Fig. 2. Measured Zeeman resonance of ^{107,109}Ag atoms in He II.

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*3 Dept. of Phys., Tohoku University
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"Hybrid-RF" sequence in β-NQR for Q-moment measurement of short-lived nuclei

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The systematic measurement of electric quadrupole moments Q of unstable nuclei would provide important information for nuclear structure studies. In Q-moment measurement, it is crucial to realize highly efficient and rapid spin-flip using the AFP (Adiabatic Fast Passage) method. We have developed a new rf-application scheme called the "Hybrid-RF" method for AFP-NQR (Nuclear Quadrupole Resonance).

When measuring the Q-moment of unstable nuclei using the β-NQR technique,[1] the nucleus is implanted in a crystal with an electric field gradient q. The resonance frequency for the implanted nucleus in a static magnetic field B_0 splits into $2I$ components due to eqQ interaction, and the transition frequency between the magnetic sublevels m and $m+1$ is given by

$$\nu_{m,m+1} = \nu_{\mathrm{L}} - \nu_Q \frac{3(2m+1)(3\cos^2\theta_{c-\mathrm{axis}} - 1)}{8I(2I-1)} \quad (1)$$

with $\nu_Q = eqQ/h$. Here ν_{L} denotes the Larmor frequency and $\theta_{c-\mathrm{axis}}$ the angle between the c-axis in the crystal and the B_0 field. An RF oscillating field B_1 needs to induce all of the $m \leftrightarrow m+1$ transitions to get the full effect of NQR. Therefore each component of the RF frequencies should be adiabatically swept to meet the corresponding frequency $\nu_{m,m+1}$ so that the population of m and $m+1$ are interchanged (AFP method).

We have previously used two methods in the RF sequence for the AFP-NQR experiment. In the first method (sequential-RF method), all $\nu_{m,m+1}$ B_1 fields are applied sequentially. When $I = 5/2$, 15 RF steps are needed and the total RF application period takes as long as 100 ms. To perform AFP-NQR for short-lived nuclei, we developed a "Mixed-RF" method in which the frequencies for all $2I$ components are swept at the same time.[2] With this method the RF application period can be as short as order of ms. However the effective B_1 field for each transition component in the mixed-wave field is reduced in inverse proportion to the number of components. Another difficulty with the mixed-RF method is that the population distribution does not change if ν_{L} is slightly changed for some reason such as B_0 drift according to a computer simulation. This is contrary to the sequential-RF scheme.

We have therefore introduced a new scheme, called the Hybrid-RF method, which is based on the sequential-RF and partially incorporates the mixed-RF method. With this method, some transitions which do not interfere each other are first induced at one time

by applying a mixed-RF wave. Another set of transitions are then induced by another mixed-RF wave. This sequence is continued until the population distribution is reversed. A possible sequence of this method in the case where $I = 5/2$ is schematically shown in Fig. 1. The number of RF steps is 9 which is less than the 15 required in the sequential-RF method, and it is easier to satisfy the AFP condition than with the mixed-RF method. Since this method is based on sequential-RF, the full AFP-NQR effect is expected to detect if the ν_L shifts slightly within the swept frequency windows.
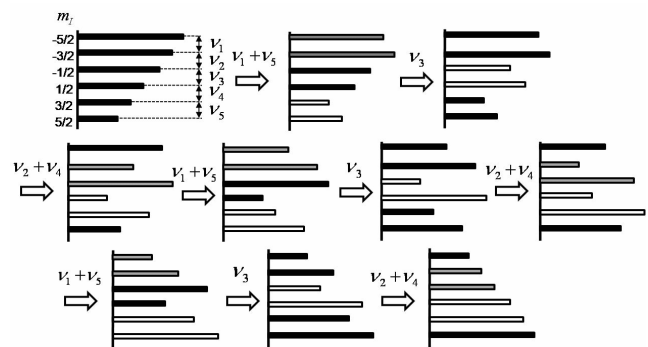
Fig. 1. Schematic diagram of hybrid-RF method showing how the population distribution is reversed.

We have tested the hybrid-RF method in an NQR-experiment with unstable nuclei ^{31}Al ($I = 5/2, T_{1/2} = 644$ ms) whose Q-moment has been previously measured. The experiment was performed at GANIL. The ^{31}Al nuclei were produced from the fragmentation of a ^{36}S beam on a Be target.[3] The beam of ^{31}Al was spin-polarized by selecting its momentum and out-going angle, and implanted into an α-Al$_2$O$_3$ single crystal. AFP-NQR was performed using β-NMR. The applied B_0 field was 5.000 kG, and the corresponding Larmor frequency was $\nu_{\mathrm{L}} = 5.824$ MHz. The applied hybrid-RF sequence was the same as in Fig. 1, where the total RF period was 72 ms and the B_1 field was 3.0 G for each transition satisfying the AFP condition $B_1 > 2\sqrt{\dot{\omega}}/\gamma_{31\mathrm{Al}}$. The measured asymmetry change with AFP-NQR was $AP = 1.4(2)\%$, which was found to be comparable with the value $AP = 1.6(2)\%$ measured using the sequential-RF method.

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Online luminosity monitor for the SCRIT experiment

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In the last SCRIT experiment, a luminosity monitor was employed to monitor luminosity. It consists of three pieces of plastic scintillation detectors, including two "finger" detectors (10cm*1cm*0.5cm) and one "backup" detector (10cm*5cm*0.5cm). Two finger detectors were put in front of backup detector and the distance between two finger detectors is 1 cm. Luminosity monitor was put on the accelerator duct 4.5 m downstream from the center of SCRIT, as shown in Fig.1. For reducing the background, we made a coincident measurement between any one of those two finger detectors with backup detector.
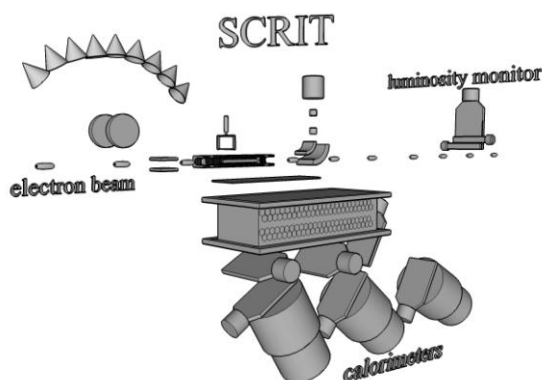
Fig.1 Sketch map of SCRIT.

Luminosity monitor utilizes forward elastic scattering where elastic cross section is huge. Two finger detectors can cover the scattering angle from 0.33 to 0.71 degree and from 0.58 to 0.86 degree. Considering Mott cross section and solid angle, the cross section of two finger detectors are 300 barn and 50 barn. Therefore, a short time measurement is needed to get enough statistics. Figure 2 shows the counting rate spectrum of one finger detector at beam current 71 mA.

The solid (dash) line is the spectra with (without) Cs ions trapped. The horizontal axis is the counting rate in the trapping time of 50 ms. Difference between two processes was only whether Cs ions were trapped or not. Therefore, the difference of two peaks should come from the events of trapped Cs ions.
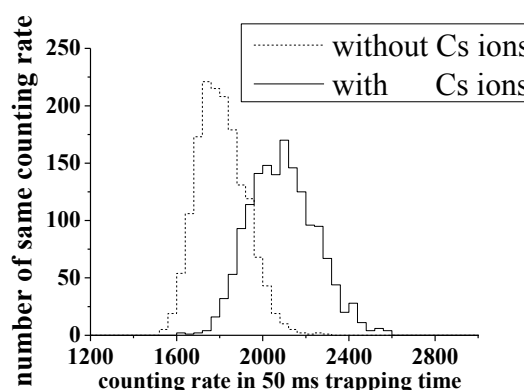
Fig.2 The counting rate spectrum.

From the counting rate difference and cross section, luminosity can be calculated from luminosity monitor, as shown in fig.3. The square points are the luminosity determined by elastic events from calorimeters and the circle points are the luminosity calculated from luminosity monitor. Two independent calculations got same results which suggest that this luminosity monitor can be used as an online luminosity monitor to monitor the luminosity during the experiment.
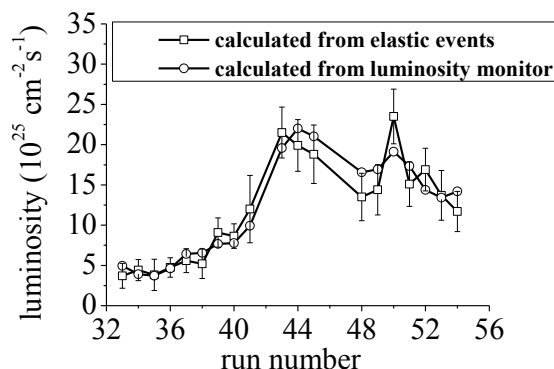
Fig.3 The calculated luminosity.

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Long-time measurement of fluctuation of magnetic field

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We are proceeding with research on uniformity and stability of a magnetic field of a sector magnet for constructing a storage ring in "Rare-RI Ring". To acheive an isochronous condition in the storage ring with a relative accuracy of 10^{-6}, a uniform and stable magnetic field in the storage ring is required. We performed a measurement of a magnetic field of a D8 magnet in a zero-degree forward spectrometer (ZDS) with a 10^{-7} relative accuracy using newly produced NMR equipment[1)2)]. We performed the measurement of a fluctuation of the magnetic field for about 170 hours this time. We also measured the temperatures of the experimental room, yoke and coil surfaces and an output of a power supply by DCCT. The measurement was performed at around the center of the sector magnet in the median plane of the magnet. We started the measurement about 20 hours after the power of the magnet had been turned on.
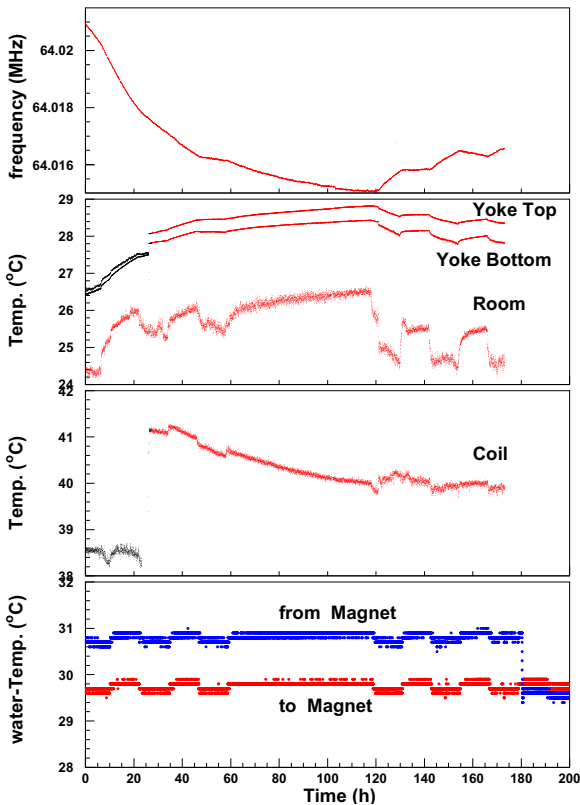
Fig. 1. Resonance frequency and temperatures

Figure 1 shows results of long-time measurement. The resonance frequency indicates the magnitude of the magnetic field. We also show temperatures of cooling water. The temperature lines of yoke and coil surfaces break at 27 hours since we improved attachment of Pt thermometers. The periodical fluctuation of the

temperature of the room is owing to the periodic operation of an air conditioner. It works from 08:00 to 20:00 in working day. The period from 60 to 120 hours was a weekend.

The fluctuation of the temperature of the room causes a fluctuation of the temperature of the yoke. From this measurement, definite correlation of the resonance frequency and the temperature of the yoke surface has been observed. Furthermore the resonance frequency (f) has a strong linear correlation with the temperature of the yoke (T). Its 1st order coefficient $\frac{df}{dT}$ is -3.6×10^{-3} MHz/K. It is -5.6×10^{-5} 1/K relatively and is the same order of magnitude as the rate of linear expansion of iron. Our result suggests that the fluctuation of the room temperature makes expansion and contraction of the iron of yoke and the expansion and contraction of the gap of the magnet affect the magnetic field.

Following this assumption, a calculation of heat conduction in an iron yoke in one dimensional space was performed. We thought it likely that a coil as a heat source and the heat flux conducts in the iron and radiates from the surface of iron. We made use of the measured room temperature as an input and chose the film heat transfer coefficient and thermal conductivity in the practical range. We show a calculated temperature of yoke surface with the temperatures of room and yoke surfaces in Fig. 2. The calculated line reproduces a characteristic of the fluctuation of the yoke surface. When unpractical parameters are used, it reproduces better. The poor reproduction might be on account of the limits of a one dimensional model.
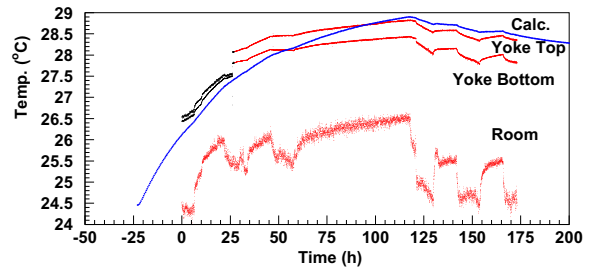
Fig. 2. The result of calculation.

For a period between 135 and 139 hours in Fig. 1, the resonance frequency and all temperatures became stable and the RMS of the frequency was 2×10^{-7} relatively. This implys that the magnetic field keeps its stability when the temperatures maintain their stability.

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Network and Computing Environment for RIKEN Nishina Center

T. Ichihara, Y. Watanabe, and H. Baba

Our computing and networking team have been operating Linux/Unix NIS/NFS cluster systems[1-2] at RIKEN Nishina Center.

Figure 1 shows the current configuration of the Linux/Unix servers at Nishina Center.

The host *RIBF* is used for the mail server and NFS server of the user home directory /rarf/u/ . A 10 TB fiber-channel RAID with fiber-channel hard disk drive (FC-FC RAID) /rarf/w/ has been connected to the *RIBFDATA01* server for data analysis. In addition, a 5.6 TB FC-FC RAID6 (/rarf/d/) has been newly added to *RIBFDATA01* to store raw data for the RIBF experiment starting in the fiscal year 2008. The *RIBF01* server is also newly installed and used together with the *RIBFDATA01*, for data analysis of the experiment at the RIBF. The RIBF Data Acquisition system (DAQ) has been developed and completed in the first phase. [3]

Postfix is used for mail transport software and Dovecot is used for imap and pop services. These software packages enable secure and reliable mail delivery. The hosts *RIBFSMTP1* and *RIBFSMTP2* are mail front-end servers used for tagging spam mails and isolating virus-infected mails. Sophos Pure Message (PMX)[4] was installed on those servers in March 2008 and has been working stably and correctly for those purposes.

The host *RIBF00* is used as an ssh login server from the outside and general-purpose computational server and a gateway to the RIBF intranet. Public-key authentication is used for ssh login to improve security.

The equipments of the Local Area Network (LAN) operated by the Advanced Center for Computing and Communication(ACCC) was replaced in January 2009. This made all Ethernet ports of the information wall sockets capable of the Gigabit Ethernet connection (10/100/1000BT).

Several wireless LAN access points (WLAP) in RIKEN Nishina Center have been added and switched to the new type WAPS-HP-A54G54[5] which supports both 2.4 GHz 11g/11b and 5.2 GHz 11a protocols. Wireless application protocol (WAP) authentication is used to ensure the security instead of wired equivalent privacy (WEP) password authentication. In total, we have installed and operated 52 WLAP.[6]

Eight temperature sensors were installed in the server rooms of the Nishina Bldg., RIBF Bldg. and in several experimental rooms of the RIBF Bldg. in September 2008. They are monitored via a web interface using the Cacti graphical tool developed by the CCJ[7] team.

An anonymous ftp server, *FTP.RIKEN.JP*, is managed and operated at RIKEN Nishina Center. A 13
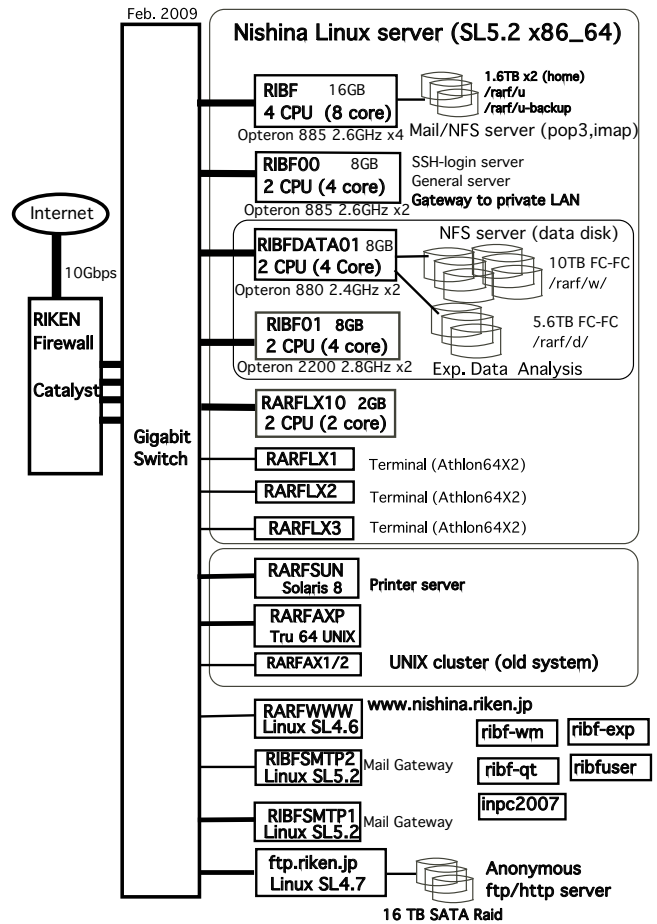
Fig. 1. Configuration of Linux/Unix servers.

TB SATA Raid system has been added to this server. Major Linux distributions are mirrored daily at the ftp server for research support.

Most of the users of Nishina Center have e-mail addresses of the following forms:

username@ribf.riken.jp or *username@riken.jp*.

The former represents an e-mail address of the mail server (*RIBF*) of RIKEN Nishina Center and the latter represents an e-mail address of the mail server (*POSTMAN*) of RIKEN ACCC.

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RIBF DAQ for Day-one Experiments

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A RIBF data acquisition (DAQ) system[1] has been developed to enable early RIBF experiments in the first several years. This system has the functions of network-distributed processing, on-line event building and analysis, hierarchical event building and parallel data readout from CAMAC and VME modules. Its event builder achieved a data processing capability of faster than 20MB/s[2].

Day-one experiments of RIBF-08, RIBF-28, RIBF-32, and RIBF-55 have recently been carried out with BigRIPS[3] and ZeroDegree Spectrometer (ZDS) based on this DAQ system. The beam-line detectors[3] installed at the focal planes of F1–F11 (Figure 1) were commonly used in these experiments, where the analog signals from a plastic scintillator and PPAC placed on the B2F experimental room were transported to the B3F measurement room via optical transceiver, and those from silicon (Si), germanium (Ge), and NaI(Tl) detectors and ion chamber (IC) were, on the other hand, converted to the digital values near the detectors. To accumulate digitized data, eleven front-end computers (FECs), which have the analog-to-digital converter modules, were installed at B2F and B3F. The allocations of the detector signals are listed in Table 1.

In addition to the eleven FECs, six servers were installed at B2F. Figure 2 shows the configuration of servers and FECs. $d02$ is the master event builder for all FECs. Two local event builders $d01$ and $ggdaq01$, installed for F11 Isomer Germanium, F8 NaI(Tl) detector array DALI2[4], respectively, allow us to acquire data independently of each other. As on-line analysis servers, $a02$, $a03$ and $d03$ were also installed.

The total number of signals of each event exceeds 1000, corresponding to the average data size ~1.6 KB/event. The event rate depended on the beam intensity and the trigger condition. For example, with 1 kcps event rate, data transfer rate is 1.6 MB/s (5.8 GB/hour), which is five-times higher than those for typical RIPS experiments.

In spite of the higher data transfer rate, the dead time of the entire system is shorter than those of previously used DAQ systems[5,6]. This is because of the following reason. The dead time of previous systems is linearly-proportional to the number of readout channels, which is ~2 ms/event with this data transfer rate. In contrast to this, the dead time of RIBF DAQ depends only on the FEC having the longest dead time thanks to the scheme of the parallel-data readout and event builder. The list of the dead time for each FEC is shown in Table 2, where three dead times of $ccnet01$

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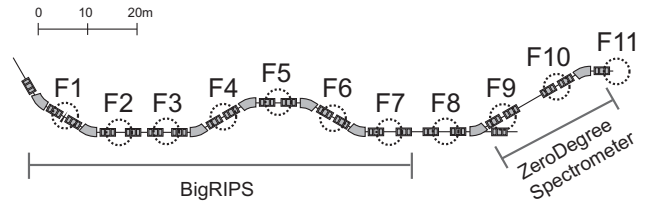
Fig. 1. The layout of the focal planes for BigRIPS and ZeroDegree Spectrometer.
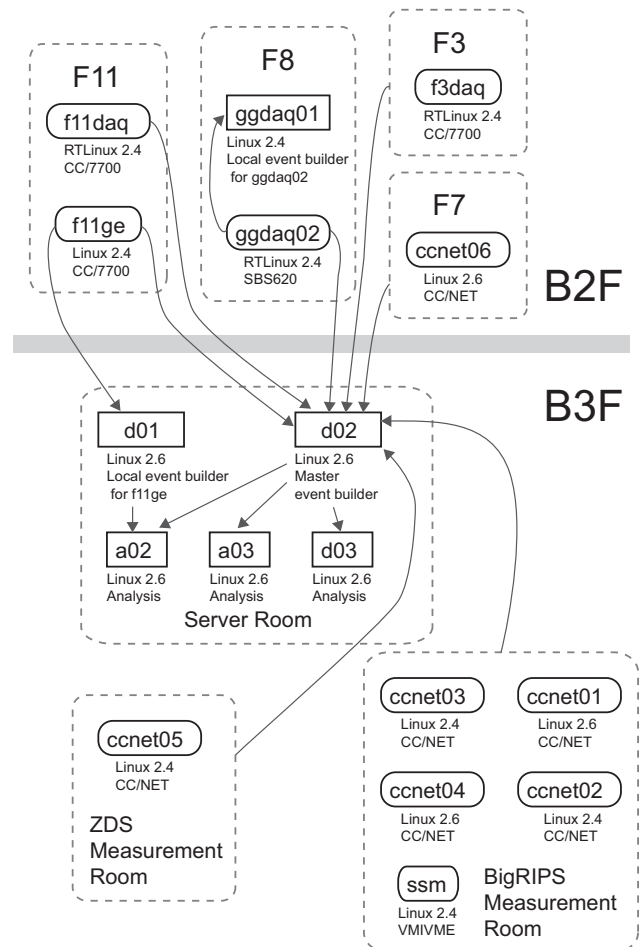
Fig. 2. The configuration of servers (rectangles) and FECs (ovals). Controllers of CC/NET and VMIVME are CPU-boards. CC/7700 and SBS620 are PCI-CAMAC and PCI-VME type controllers, respectively.

are shown separately. The detector configuration covered with $ccnet01$ differs according to beam tuning and experiments. Their dead times for the whole DAQ system are 350 and 280 μs/event, respectively. In these

Table 1. The allocations of the detector signals. *ccnet01–05* were installed on B3F measurement room. Other FECs were placed in B2F experimental room.

Detector		FEC
F1, F2, F3, F4, F6 Plastic and PPAC	⇒	*ccnet01*
F3 Si	⇒	*f3daq*
F5 Plastic and PPAC	⇒	*ccnet02*
F7 Plastic and PPAC	⇒	*ccnet03*
F7 Si, Ge and IC	⇒	*ccnet06*
F8 and F8' Plastic and PPAC	⇒	*ccnet04*
F8 NaI(Tl) detector array (DALI2)	⇒	*ggdaq02*
F9, F10, F11 Plastic and PPAC	⇒	*ccnet05*
F11 Si and IC	⇒	*f11daq*
F11 Ge	⇒	*f11ge*

Table 2. The dead time per 1 event for each FEC. Third configuration marked with a * was prepared but not used. ssm was the front end for start/stop control and scaler. It did not affect the dead time of the system.

Name	Dead time	Remarks
ccnet01(a)	350 μs	beam tuning (F1–F6)
ccnet01(b)	280 μs	RIBF-08, 28, 32, 55 (F3–F6)
ccnet01(c)	130 μs	RIBF-28, 32 (only F3)*
ccnet02	120 μs	
ccnet03	130 μs	
ccnet04	180 μs	
ccnet05	230 μs	
ccnet06	150 μs	
f3daq	180 μs	
f11daq	210 μs	
f11ge	∼200 μs	depends on gamma-ray rate
ggdaq02	∼200 μs	depends on gamma-ray rate
ssm	——	start/stop control and scaler

cases, the bottleneck was the performance of *ccnet01*. The dead time of the system can be improved to as short as 230 μs, which is limited by *ccnet05*, in the configuration of *ccnet01*(c) given in Table 2.

The dead time of each FEC depends on the number of readout channels, the conversion time of ADC, and the interrupt latency of the operating system. If the number of readout channels per FEC is small and the conversion times of all ADCs are short enough, it is possible to achieve a dead time of less than 100 μs/event. The performances of CAMAC and VME controllers are important to reduce the dead time of FEC. Thus, a device driver for CC/NET has been newly developed. There are two hardware versions of CC/NET. The former version is running under Linux 2.4, whereas the latter is running under Linux 2.6. Their performances are summarized in Table 3. CC/NET has the functions of programmed input/output (PIO) block transfer mode and direct memory access (DMA) block transfer. The process time of these block transfer modes are determined

Table 3. The performance of the new CC/NET device driver. CC/NET has a block transfer mode only. The interrupt service routine (ISR) latency is the delay time coming from the period between the trigger signal reception and the actual start of the routine.

	Linux 2.4	Linux 2.6
Block PIO	3.6 μs/ch + 2.4 μs	2.6 μs/ch + 1.7 μs
Block DMA	1.2 μs/ch + 9.9 μs	1.2 μs/ch + 6.7 μs
ISR latency	21.7 μs	30.0 μs

by the number of readout channels and overhead time. The process time of CC/NET is much higher than other CAMAC controllers. The performances of other CAMAC and VME controllers such as TOYO CC/7700, Kinetic 3922, Wiener VMEMM, and SBS 620, have been reported in Ref. 7.

In summary the RIBF DAQ system has been developed and it functioned as designed in the day-one experiments. In spite of the large data transfer rate of 1.6 KB/event, the dead time was effectively suppressed to 280 μs/event. The performance of the system is sufficiently high to cover most of RIBF experiments.

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PHENIX silicon vertex tracker project

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We are constructing a silicon vertex tracker (VTX) for the PHENIX experiment at RHIC. The primary purpose of the detector is to carry out precise measurements of heavy-quark production (charm and beauty) in $A + A$, $p(d) + A$, and polarized $p + p$ collisions. The main physics topics addressed by the VTX are as follows.

- Probing high-density partonic matter

  ○ Energy loss of heavy quarks (charm and bottom) in dense matter
  ○ Elliptic flow of heavy quarks in dense matter
  ○ Precise measurement of open heavy-quark production
  ○ Modification of jets by medium effects

- Measurements of gluon spin structure of nucleon

  ○ $\Delta G/G$ with heavy-quark production
  ○ $\Delta G/G$ with γ-jet measurement

- Nucleon structure in nuclei

  ○ Gluon shadowing over broad x-range

These are key measurements that are required for future RHIC programs, both for the study of QGP in heavy-ion collisions and for the measurement of the nucleon spin-structure functions.

The VTX detector consists of two inner layers of silicon pixel detectors[1] and two outer layers of silicon strip detectors. The detector covers pseudo-rapidity $|\eta| < 1.2$ and azimuth $\Delta\phi \approx 2\pi$. The project is funded by RIKEN, US DOE, and Ecole Polytechnique. The US side of the project was started in US FY07. The total budget is 4.7 M US dollars over four years (FY07-FY10).

The main points of progress this year are as follows.

- The first annual review of VTX was held at BNL in June 2008.

- Fabrication of the pixel buses[2] is under way.
- Q/A of the pixel sensor module is on going.
- Development of a pixel detector assembly system is complete.[3]
- A final prototpye pixel ladder was fabricated with a production pixel bus and using the pixel assembly system.
- Q/A system for pixel ladders was developed.[4]
- Performance of the pixel detector was tested at a beam test at FNAL.[5]
- Development of the pixel read-out electronics is complete.[7] Fabrication of the SPRIO read-out board is under way at Ecole Polytechnique. Fabrication of the pixel FEE boards has been started at Stony Brook.
- Q/A of the strip sensors is near completion.
- Signal to noise ratio of 10 has been achieved for the strip detector prototype based on a ROC3 read-out card in a bench test as well as in the FNAL beam test.[6]
- Development of the read-out electronics for the strip system is underway. Prototypes of the RCC board, the LDTB board, the strip bus, and pre-production ROC will produced soon.[7]
- Fabrication of pixel staves (mechanical support+cooling) is on going at LBNL and will be completed soon.
- On the software side, update of simulation software of the VTX systems[7] and physics simulation of VTX[8] are on going.

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Spin physics capability with silicon vertex tracker for PHENIX

M. Kurosawa [*1] for the PHENIX vertex collaborations

PHENIX is an experiment aiming to study the spin structure of nucleons and hot and dense matter at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). The PHENIX detector will be upgraded with the introduction of a silicon vertex tracker (VTX) to extend its physics capability[1] in both the spin and heavy ion program. One of the roles of the VTX in the spin program is to determine x-dependence of $\Delta G/G$ with γ-jet correlation over a wide x range. The γ-jet measurement is a good probe to determine x-dependence of $\Delta G/G$ because the reaction is dominated by Compton $qg \rightarrow \gamma q$ scattering. A detector with large acceptance and good position resolution is required in order to reconstruct the jet-axis in γ-jet measurement. The VTX has good position resolution ($< 50~\mu m$) and covers a large acceptance in a pseudo-rapidity range $\eta < 1.2$ and almost $2~\pi$ in azimuth.

In the future, integrated luminosity is expected to reach 300 pb^{-1} at $\sqrt{s}$=500 GeV. This report describes the simulation results of a longitudinal double-spin asymmetry A_{LL} for γ-jet event with VTX detector at this expected luminosity.

The γ-jet production events were generated using the PYTHIA Monte Carlo program.[2] Jet axis was reconstructed by using a simple cone algorithm.[3] Direct photons were reconstructed with the finely segmented electromagnetic calorimeters in PHENIX detector.

With the current PHENIX detector, Bjorken x gluons (x_g) are evaluated using only the transverse momentum of direct photon, as described by the following equation.

$$x_g = \frac{2P_T}{\sqrt{s}} \qquad (1)$$

With the VTX detector, x_g can also be calculated by using jet axis information. The x_g is the smaller of x_1 and x_2 in the following equation.

$$x_1 = \frac{P_T}{\sqrt{s}}(e^{+\eta_{jet}} + e^{+\eta_\gamma}), \quad x_2 = \frac{P_T}{\sqrt{s}}(e^{-\eta_{jet}} + e^{-\eta_\gamma})$$
$$x_g = \min\{x_1, x_2\} \qquad (2)$$

Figure 1 (a) and (b) show the scatter plot of true x_g from PYTHIA and reconstructed x_g with VTX and without VTX, respectively. Since the jet axis can not be measured without VTX, there are discrepancies between true x_g and reconstructed x_g within the region of low $x(\gamma)$ in Fig. 1 (a). When measuring the jet axis with VTX, however, the reconstructed x_g is close to true x_g in Fig. 1 (b).

Figure 2 shows the simulated A_{LL} of gluon as a function of x_g assuming $\Delta g = g$, $\Delta g = -g$ and the GRSV

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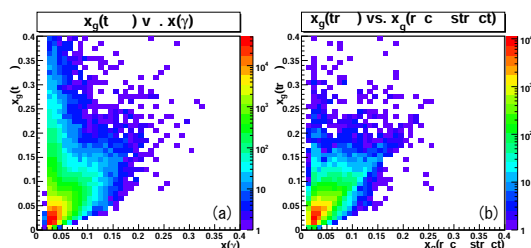
Fig. 1. Frame (a) and (b) show PYTHIA results comparing true x_g from PYTHIA and reconstructed x_g with VTX and without VTX, respectively. x_g(true) is true x_g. $x_g(\gamma)$ and x_g(reconstruct) are obtained from Eq. 1 and Eq. 2, respectively.

standard model.[4] The polarization of incident protons was assumed to be 70 %. Vertical error bars in the plot represent statistical and background subtraction errors. Horizontal error bars indicate reconstructed uncertainty of x_g.
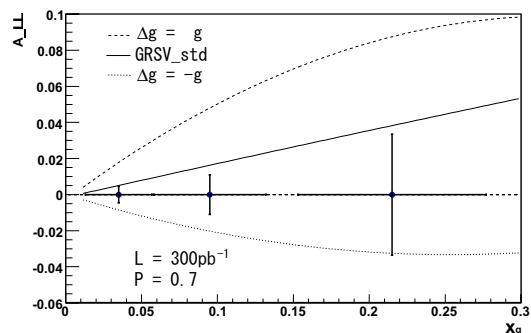
Fig. 2. Simulated A_{LL} of gluon as a function of x_g. Dashed, dot-dashed and solid lines correspond to A_{LL} assuming $\Delta g = g$, $\Delta g = -g$ and the GRSV standard model, respectively.

PYTHIA simulation of γ-jet production was performed under the conditions $\sqrt{s} = 500$ GeV and L = 300 pb^{-1}. Using VTX improved the x reconstruction especially in the lower x_g region. The A_{LL} was estimated as a function of x_g.

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Silicon Pixel Detector for the PHENIX Vertex Tracker[†]

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The silicon Vertex tracker (VTX) will be installed
in 2010 to PHENIX experiment at the Relativistic
Heavy Ion Collider (RHIC) to enhance physics capa-
bility in both spin and heavy ion program. The VTX
will be implemented very close to the collision points
and cover $\eta \mid \leq 1.2$ and $\phi \sim 2\pi$ by four layers of silicon
sensors.[1] It will be able to identify the heavy quark
production from light quarks by measuring a displaced
vertex due to the longer life time of charm and bottom
quarks, whose $c\tau$ ranges 100 to 400 μm. The jet will be
identified by measuring momentum of charged hadrons
within its larger acceptance.

The VTX consists of pixel detectors on inner two
layers and stripixel detectors on outer two layers, which
are shown in Fig. 1. We, RIKEN group are in charge
of 30 pixel ladders, which is the minimum replaceable
module of the detector. This article describes the sta-
tus of the pixel ladders.

The pixel ladder consists of four sensor hybrids, a
support stave, and two readout bus. The pixel size of
the sensor is $50 \times 425 \ \mu m^2$, which is shown in Fig 2
as small black box. One sensor has $256 \times 32 \times 4$ and
is connected to four ALICELHCB1 chips by the bump
bonding technology. A signal from the sensor are con-
verted to binary hit data through a preamplifier and a
discriminator. These binary hit data as digital signal
are transmitted to a Silicon Pixel Read-Out (SPIRO)
board via an extender. The SPIRO board multiplex
data from eight of ALUCLHCB1 chips, and transmits
them to a Front End Module (FEM) thorough 1.6Gbps
serial optical link.[4] Up to the SPIRO will be imple-
mented near collision points, so they must be compact,
thin, and radiation hard. The FEM receives the hit
information from multiple SPIRO boards and trans-
mits them with format transformation to the PHENIX
DAQ system.

The readout bus and the extender[2] was made with
polyimide-base flexible printed circuit. The bus that
is 1.4cm wide, 25cm long, and 300 μm thick, consists
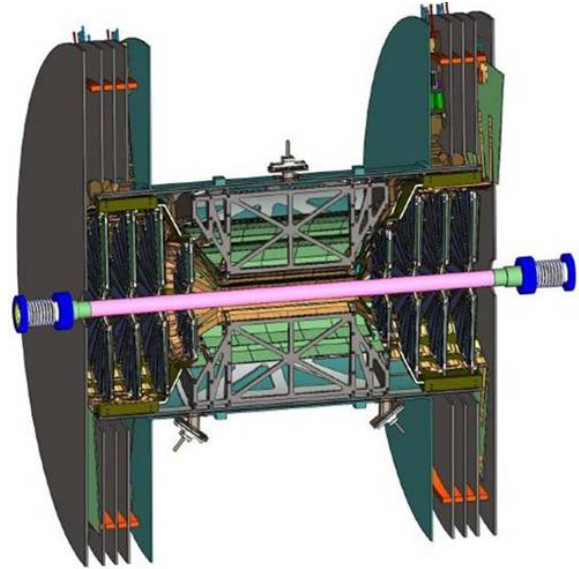
Fig. 1. PHENIX Vertex Tracker: Cut view on the Z-ϕ
plane. The pink tube is a beam pipe. The two lay-
ers of pixel sensor and two layers of stripixel sensors
are arranged in a concentric pattern.
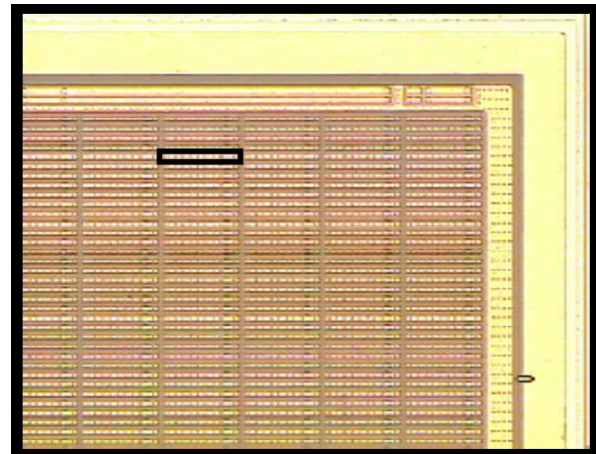
Fig. 2. Pixel sensor: One pixel is shown as black small
box, whose size is $50 \times 425 \ \mu m^2$. The generated parti-
cles from the proton-proton collisions are boosted in the
beam direction. The transverse momentum from beam
axis has more physics information. It requires asym-
metric spatial resolution to minimize the total number
of readout channel.

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of four signal layers, which include 186 signal lines, and two power layers. The bus and sensor hybrid are connected by bonding wires. The extender has two layers for signal lines, which are sandwiched by power layers and a thin shield layer. The connection between the bus and the extender are done by two fine pitch connectors. The cross talk on a trigger signal line was caused by the clock signal line, which was located on the back of the trigger line. These lines were isolated by the 50 μm thick polyimide film. In addition to moving all lines from the backside of the trigger line, all backside lines were laid as cross-stitched. The extender with the new design was made and confirmed having no cross talks.

The four sensor-hybrids were lined up within $10\mu m$, and then were glued to the support stave. Two readout buses were glued on them. After glue was cured, the sensor-hybrids and the buses were connected by the $25\mu m$ diameter aluminum boding wires. Fig. 3 shows the full pixel ladder. Some of the wires have intermittent electrical current flow which is synchronized to the data taking triggers. The trigger rate is up to 20 KHz at the PHENIX DAQ environment. We observed wire vibration with resonance structure in the 1T magnetic field.[3]. The frequency of the resonance peak is around 5 KHz. So the wire may be broken in the real PHENIX environment. Therefore the wires are encapsulated by two types of glues. The low viscosity glue should encapsulate entire wires. The high viscosity glue is used for barriers preventing low viscosity one to flow out. The procedure for the encapsulation is established with the realistic pixel ladders.

The assembled pixel ladders have to be tested for functionality electrically with the extender, the SPIRO board and the FEM. The FEM was controlled by the PC with Microsoft Visual Basic environment. The original program was written for the hardware development. The functional test should be done automatically. We reorganized the original program.[5] All configuration such as threshold of discriminating a signal from noises, pipeline delay length for the trigger timing, and so on are downloaded via JTAG control. The specified electric charge was injected into the preamplifier input and then hit data were retrieved. The threshold curve was obtained by scanning threshold of the discriminator. The threshold and noise characteristic of the each pixel channel were obtained. Also the sensor hybrid was irradiated by the β-ray from ^{90}Sr source and then hit data were read out. The hit map was drawn and confirmed most of the pixels on the sensor were functional.

A telescope array of three pixel ladders were tested with 120 GeV/c proton beam at the Fermi National Accelerator Laboratory[6] with stripixel ladders.[7] The pixel ladders were connected to the FEM via SPIRO boards. The FEM sent data to the data acquisition system which emulated PHENIX data acquisition system. Event trigger was generated by the coincidence among two scintillation counters on upstream and downstream of the pixel telescope, and was required a hit on each three layers at minimum. The trigger rate was around 40Hz and 19K events were accumulated in the storage successfully.

In conclusion we have finished the development phase of the pixel ladders, confirmed their performance by using high energy proton beam. First mass production batch will be started in the early 2009.

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Fig. 3. Assembled full pixel ladder: It consists from one carbon fiber stave, four sensor module, and two readout buses.

Development and production status of a fine-pitch and low-material-budget readout bus for the PHENIX pixel detector

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The PHENIX detector system at the relativistic heavy ion collider (RHIC) at the Brookhaven National Laboratory will be upgraded by installing a four-layer silicon vertex tracker (VTX) by the summer of 2010.[1] The VTX consists of two inner silicon pixel detectors and two outer silicon strip detectors. The VTX will enhance the physics capabilities to enable the investigation of new hot and dense nuclear matter in heavy-ion collisions and the structure of the proton spin in polarized proton-proton collisions at the RHIC by identifying heavy quarks via the measurement of the displaced vertex.[1] Our group is responsible for developing and fabricating the Silicon Pixel ladder.

The signals from pixel sensors are processed using bump-bonded readout chips and converted to binary data. One readout chip has data of 32-bit × 256 depth. The binary data are transferred to a SPIRO board[2] via fine-pitch and low-material-budget Pixel Bus. The signal on the SPIRO board is converted to a serial optical signal and transmitted to the PHENIX DAQ system. The Pixel Bus has been developed and is in the production phase. The status of the Pixel Bus is described in this report.

In principle the Silicon Pixel Detector has five constraints on the detector and the production sides: ∼ 50 μs of detector readout time, avoidance of mechanical conflict with the neighboring detector sector, minimization of the multiple scattering and photon conversions, and ease of Pixel Bus production and handling on the production side. For the detector readout time, we have chosen to expand the parallel 32-bit data width in the original design of ALICE[4] to 128-bits. First, we modified the digital PILOT chip, which has a 2 × 32-bit data bus width. The digital PILOT chip controls readout chips and multiplexes data from the chips.[2] By using two digital PILOT chips for two sensor modules an approach, which is called a half-ladder,[5] the Pixel Bus will have a 128-bit data bus width. Four readout chips (4 × 32-bit data width) can be read in parallel on the half-ladder. However, this expansion requires a circuit with a layout four-times more dense than layout from the original ALICE design on the bus. Moreover, a bus width of 13.9 mm is resuired to avoid mechanical conflict with the neighborhood, a bus width of 13.9 mm is required. In order to minimize multiple scattering and photon conversion in the detector, the Pixel Bus has to be made as thin

as possible with available technology. Fourth, to facilitate production and handling of the bus, it should be made with Flexible Printed Circuit board (FPC) technology, in which the board is made from a conductor of copper and aluminum, and a polyimide insulator. Finally, two types of Pixel Bus are necessary for detector construction, i.e., the right side and left side bus. The difference between these buses is their signal and power connector positions. The circuit on the buses has exactly the same functionality. The right Pixel Bus has connectors on the right, the left Pixel Bus has them on the left. The development of such a fine-pitch FPC is a challenging but key component of the project.

We developed a new copper-aluminum-polyimide FPC that has a 128-bit data bus width. The Pixel Bus has the advantage of not only enabling a four-fold increase in the data bus width, but also reducing the material budget. For our bus, we are aiming for less than 0.28% of X/X_0 in the radiation length. The bus has six layers that consist of copper, aluminum and polyimide films. It contains two signal layers, two via layers for manufacturing purposes, a power and a ground layer. Two fine pitch connectors on the bus are for connection with a Bus Extender connected to a SPIRO board. The connectors are for control and data signals. The bus contains 188 longitudinal lines in total. The size of the bus is 13.9 × 250 mm^2. Hence, one signal and control line is 30 μm in width and the interval between line and line is 30 μm in minimum with 3 μm thickness copper.[7,8]

In the production phase, we have attempted to improve the bus production yield. We succeeded in increasing the yield from a very low level (< 10%) to ∼ 80% by two methods. The first method is a modification of the via process. A via is an interconnection between different layers, i.e., a through hole with copper plating. The second method is to reduce "Micro Short" between a line and a ground plane by using a new layout. The Micro Short means a bridge made by a residue of copper between a pattern and pattern.

In the via process, laser drilling is done by ∼ 10 times with a fine-adjusted laser output. Because in a via hole made by a laser by one time, a polyimide film is greatly melted by the generated heat and the reflection at the higher layer output. Consequently the via hole diameter is irregular in polyimide and copper regions. The irregular diameter region causes a defect in the Au plating process for the vias. The circular via hole is changed to an oval shape. This modification

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allows the plating fluid to easily penetrate into the via hole.

In the new layout, the distance between a line and the ground layer increased by more than 100 μm from the first design. With this layout, the residue of copper around the region is removed completely in the etching process, and the Micro Shorts on the bus disappear.

To evaluate performance, line resistance has been measured using an Agilent 4263B LCR meter and a micro-positioner with a probe needle. Figure 1 shows the measured resistance divided by the line length for the right and left side bus. The mean value is 0.174 Ω/mm; the sigma is 0.017 Ω/mm for the right side bus; the mean value is 0.191 Ω/mm; and the sigma is 0.011 Ω/mm for the left side bus. The calculated value is 0.13 Ω/mm $\sim$ 0.17 Ω/mm. Thus the fabrication quality is excellent.
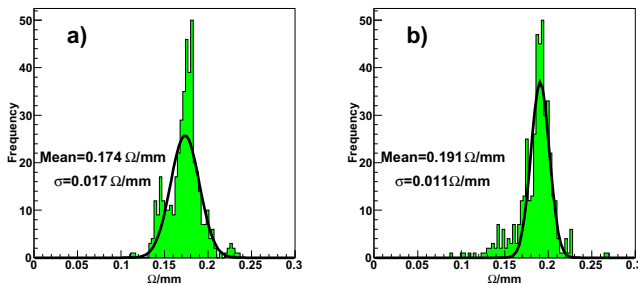
Fig. 1. Resistance distribution of the right and left Pixel Bus. a) is the right side bus, b) is the left side bus.

A half-ladder and a full-ladder were successfully fabricated using the buses.[5] In 2008 we had access to a test beam to check the functionality at the Fermi National Laboratory. A telescope consisting of three layers of pixel ladders was used, and irradiation was done with a 120 GeV proton beam was irradiated.[9]

A total 19542 events were collected and 7308 tracks were reconstructed.

In summary, we have successfully developed and produced a very fine pitch and low-material-budget readout bus for the VTX upgrade. The production yield has been increased by improving the via process and line layout. This is shown by the measured resistance in the Pixel Bus. The pre-production ladder has been successfully fabricated, and performance was checked in the test beam at FNAL in 2008. Finally, the mass production of the Pixel Bus will start at the beginning of 2009.

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Development of quality assurance software
for the silicon pixel ladder in the PHENIX Vertex Tracker

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The PHENIX detector at RHIC-BNL will be upgraded with a silicon vertex tracker (VTX) surrounding a beam pipe with four cylindrical layers[1]. The inner two layers are silicon pixel detectors (SPDs) and the outer two layers are silicon strip detectors. As part of the plan upgrading the PHENIX VTX, the RIKEN group is developing the SPD. The SPD is made up of 30 ladders, each of which consists of a thermal plate, four sensor hybrids and two pixel buses[2]. A sensor hybrid is an assembly of a silicon pixel sensor and four readout chips (ALICE1LHCb) which were bump-bonded with 20-μm-diameter bumps to the sensor. The readout chip has 8192 pixel cells arranged in 32 columns and 256 rows. The pixel size is 50 μm $\times$ 425 μm. The pixel bus is a copper-aluminum-polyimide base flexible printed circurit board. A signal from the silicon pixel sensor is read out through the readout chip and the pixel bus. For the production of the ladder, a quality assurance (QA) test of the ladder is required to ensure that it can be implemented in the PHENIX. This report describes the development status of ladder QA software.

The set up of the ladder QA system is shown in Fig. 1. A half ladder is connected to a Silicon Pixel Interface Read Out module (SPIRO) board[3] with a flexible printed circuit board (the pixel bus and bus extender[4]). The SPIRO board supplys reference voltages to read out chips on the sensor hybrids, serializes data from two sensor hybrids on a half ladder and sends out the data to a front end module (FEM) via optical cables. The FEM sends out the data to a PC via USB1.1 data link.

The ladder QA software controls this equipment using a Visual Basic program and analyzes test results with the ROOT analysis tool[5] in the Microsoft Windows XP environment.

In the QA procedure, a chip is classified according to the threshold and the noise levels. As for the levels, we adopt mean levels calculated from the data for all of the pixels in the chip. The following method was applied to measure the threshold and noise levels for a pixel. A specific amount of charge was injected into the relevant preamplifier for a pixel 100 times. The efficiency of detecting the charge is the ratio of the event with a response. Nineteen different amounts of charge were examined in a similar way for measurement of the turning on curve as shown in Fig. 2, where the efficiency is plotted as a function of charge. The data was fitted with an error function (a line). The derivation of the function gives a gaussian distribution characterized by two parameters, mean and standard deviation. These two parameters correspond to the threshold and the noise levels for the pixel, respectively. The noise level is also used to identify a noisy pixel.

Fig. 1. Set up of ladder QA system.
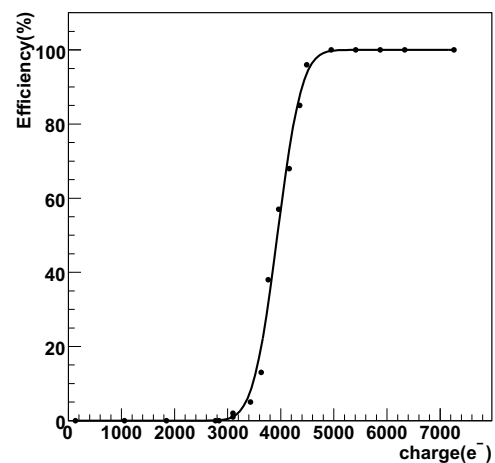
Fig. 2. A typical threshold curve obtained for a pixel. Horizontal axis is the charge value injected into the preamplifier input. Vertical axis is the efficiency for each injected charge.

In the present procedure, the data for pixels in the same row was taken simultaneously as shown in Fig. 3 (a). Therefore, the data for a whole chip has to be

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transferred as many times as the number of rows. Based on the time we used to take the data for 320 pixels, it is estimated that this method takes ~17 hours per one chip. Our goal is to finish the scan test for a chip in less than one hour. The reason it is time consuming is mainly due to the access time of 100 ms of USB1.1 link. Consequently, the threshold scan takes at least 100 ms × 100 test pulses × 19 points × 256 rows ~13 hours/chip. However, if data is taken "column by column" instead of "row by row" as shown in Fig. 3 (b), time taking data is expected to be reduced by as much as a ratio of 256 to 32. Furthermore to reduce the amount of access, it is important that a data buffer is added in the FPGA on the FEM. For example, if 100 buffers are prepared, the data transmission via USB1.1 link will reduce one-hundredth. The data transmission time of 13 hours/chip is then reduced to 8 minutes. Through these improvements, we estimate that the data transmission time will be a few minutes/chip.
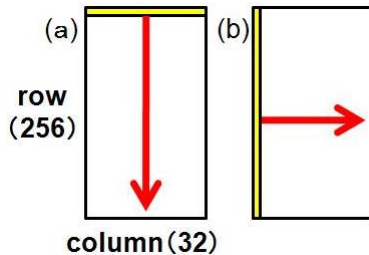
Fig. 3. The scanning directions are indicated by arrows. The number of rows and columns are 256 and 32, respectively. (a) The data for one row is taken one at a time. (b) The data for one column is taken one at a time.

In summary, the basic parts of the ladder QA software have been developed. The QA time will be improved, and as a result it will take a few hours in total for one half ladder. We expect that the QA software will be completed in advance of mass production of the half ladder.

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Development of an encapsulation procedure for the first PHENIX pixel ladder in the production version †

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The Relativistic Heavy Ion Collider (RHIC[1]) at Brookhaven National Laboratory (BNL) enables polarized p-p collisions at $\sqrt{s}$ up to 500 GeV and heavy nuclei at $\sqrt{s_{NN}}$ up to 200 GeV. The Pioneering High Energy Nuclear Interaction eXperiment (PHENIX[2]) is one of the two main experiments at RHIC.

We have been constructing a silicon vertex tracker (VTX[3]) for the PHENIX which will enhance the physics capabilities of the PHENIX central arm detectors. The purpose is to measure the heavy flavor mesons which carry direct signals from Quark Gluon Plasma in heavy ion collisions and fundamental information on gluon polarization in polarized p-p collisions.

The VTX consists of two types of silicon detectors: a pixel detector and a strip detector.[4] A pixel ladder is the basic unit of the pixel detectors. There are 10 and 20 pixel ladders in the first and second layer of the VTX, respectively. A pixel ladder is made of four sensor modules, two readout buses,[5] and a stave which provides mechanical support and cooling.

After assembly[6], four sensor modules and two buses are connected electrically by wire-bonding. The 1848 Al wires, 25 μm in diameter and roughly 4 mm long, are wedge-bonded at a 120 μm pitch by a bonder machine, the K&S 8060.

We evaluated the effect of resonant vibration on bonding wires induced by Lorentz force[7] with mock circuits wire-bonded in 0.8 T magnetic field, corresponding to the actual environment where the VTX will be installed, using the magnet in the RIKEN Nishina Center. The ends of the bonding wire were connected to a GTL pulse generator and 50 Ω terminated register. A monochrome CCD video-camera equipped with a telephoto lens was located $\sim$ 0.6m away from the circuit to prevent it from being influenced by magnetic fields. The vibration was observed as in Fig 1, where the horizontal thin lines are bonding wires which connect the ends of the left and the right electrodes. The vibration was recorded in a movie for 3 seconds in the AVI format with a capture board in the PC. GTL pulses were sent for 2 seconds (on signal) and nothing (off signal) was sent for 1 second.

On and off signal frames were integrated separately over the two-dimensional histograms of pixels for brightness. Next, each integrated two-dimensional histogram was sliced at the maximum resonant plane

of the bonding wire into a one-dimensional histogram. Each histogram, representing the cross-section of the resonant plane, was fitted with a Breit-Wigner function convoluted single Gaussian and a first-order polynomial function. In this fitting, the sigma of the convoluting Gaussian for the on signal histogram was fixed to the value of the sigma obtained by the fit for the off signal histogram. We defined the $\mathrm{FWHM_{on}}$ and $\mathrm{FWHM_{off}}$, where the FWHM stands for the full width at half maximum of the fitted Breit-Wigner, obtained from the fitting the on signal and off signal histograms, respectively. The points in Fig 2 indicate the ratio of $\mathrm{FWHM_{on}}$ to $\mathrm{FWHM_{off}}$ at various frequencies, where the fitted empirical function f is defined by Eq (1) and described as a solid line with fitted parameters.
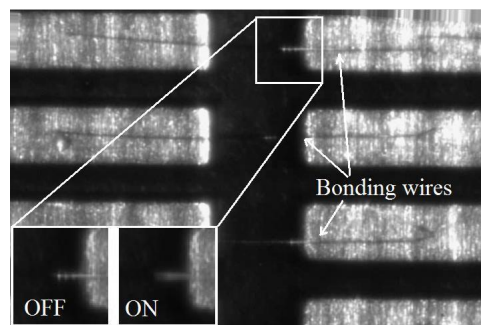
Fig. 1. Observed vibration of the bonding wire.

$$f = 1 + B.W. = 1 + \frac{(\gamma^2/4)H}{(\omega - \omega_0)^2 + (\gamma^2/4)} \qquad (1)$$

The maximum vibration of the wire exists around 5.9 kHz which is close to the L1 trigger-rate in the PHENIX. Therefore, we concluded that the bonding wires should be encapsulated. An encapsulation method using two encapsulants, Sylgard 186 and 184, was developed using a dispensing robot. Dispensing just above the wires, the encapsulants can not stay around the wires. We solved this problem by forming a dam using Sylgard 186, which has a high viscosity, near the neck of the wires at the bus side. After curing, the ladder was tilted and filled with Sylgard 184 as shown in Fig.3.

We successfully assembled a first pixel ladder, shown in Fig 4, using the procedure in this report and the actual component in July, 2008. Table 1 shows a breakdown of the time required to assemble a ladder,

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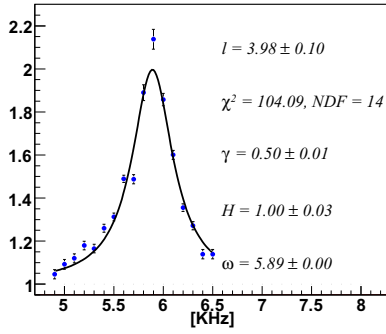
Fig. 2. Frequency dependence of the $\mathrm{FWHM_{on}}/\mathrm{FWHM_{off}}$, where l is the length of the bonding wire, γ is the FWHM, H is the height and ω_0 is the resonant frequency. The solid line indicates the fitted function f.
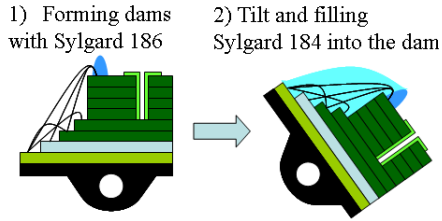
Fig. 3. Developed encapsulation method.

Fig. 4. Assembled pixel ladder in the container.

Procedure\Scheme	Past		Current	
	hour	day	hour	day
Sensor alignment	8×3		0.5	
Q/A	→		0.5	
Gluing sensors		3	1	1
Cure time	12×3		12	
Gluing buses	8×2		1	
Cure time	12×2	2	12	1
Q/A	→		0.5	
Wire-bonding	→	1	8	1
Forming dam			1×3	
Cure time			12×3	
Filling encapsulant	→	4	1	4
Cure time			12	
Total	161	10	87.5	7

Table 1. Assembly time of a ladder using current and past scheme.

comparing the current and the past assembly schemes. Past trial assemblies of half ladders were performed manually by skillful engineers. The time needed for wire-bonding is conservatively estimated at 8 hours, including tuning of the bonder machine for every ladder. The time for encapsulation is estimated at 52 hours which consists of forming the dam in three steps and the cure time. In total, 87.5 hours and 161 hours are required to assemble a ladder with the current and the past schemes, respectively. The number of the days to deliver a ladder is 7 days with the current scheme and 10 days with the past scheme. Most of the time is used to cure the adhesive and encapsulant in the ladder placed on the stave fixture. The waiting time can be reduced to use six stave fixtures and to pipeline the procedure in Table 1. Therefore, the total assembly time of 87.5 hours can be reduced to 27.5 hours, after subtracting the curing time of 60 hours. The number of days to deliver of a ladder can be compressed to 2 days. The new pipeline assembly scheme can conservatively produce 40 ladders in four months.

We have confirmed that the current method produces ladders with higher precision and efficiency than the past assembly that required high cost and time.

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Implementation of charge sharing and clustering in simulator of PHENIX silicon vertex tracker

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The PHENIX experiment is being carried out at RHIC to investigate the property of hot and dense hadronic matter using heavy-ion collisions and the spin structure of the proton using polarized proton-proton collisions. The Silicon Vertex Tracker (VTX)[1] is mandatory to improve the capabilities of the PHENIX experiment. It provides (1) a precise vertex measurement, which enables us to separate charm and bottom (heavy flavor) quarks, and (2) a charged-particle tracking with large acceptance, which enables us to measure charged particles to reconstruct the jet at mid-rapidity.

The VTX will be installed close to the collision point and cover a pseudorapidity region $|\eta| < 1.2$ and a azimuthal angle $\Delta\phi \approx 2\pi$, where the acceptance of the PHENIX Central Arms is currently $|\eta| < 0.35$ and $\Delta\phi = 90° \times 2$[2]. The VTX consists of two pixel layers at inner and two stripixel layers at outer within 14 cm from the beams. One layer is segmented into 10 to 20 ladders, each of which covers a part of ϕ angle. The sizes of pixels are 50×425 μm^2 in pixel layer and 80×1000 μm^2 in stripixel layer, where the longer side is parallel to the beam axis (z). Stripixel channels are read out in two directions, x-strip (parallel to beam direction) and u-strip (tilted by $\arctan(80/1000) = 4.6°$), and all channels in each direction are summed up into one readout.

In parallel to the detector construction, simulation studies based on the GEANT detector simulator are being carried out. It is indispensable to evaluate a realistic performance expected under the current detector configuration, such as position resolution and S/N. We implemented a realistic charge-sharing and clustering algorithms for it.

Charges deposited by a particle can be shared between neighboring strips particularly when the particle is incident non-vertically. The charge-sharing algorithm divides charges by the fraction of the path length in each strip. The clustering algorithm will deal with real data in the future as well as simulated data, and so far the clustering in stripixel layer has been implemented. Neighboring strips that have an ADC value above a threshold are gathered into a group. The position of a group is defined as the ADC-weighted positions of all strips in the group; $x_{group} = \sum_i (ADC_i \cdot x_i)/\sum_i ADC_i$. The same grouping is independently done with u-strips, and all crossing points of x-groups and u-groups are regarded as reconstructed hits. Figure 1 shows an example of the result of clustering, and Fig. 2 shows the position resolution, i.e. the difference between true and reconstructed hit positions. It is better than $width/\sqrt{12}$ as expected when charges are shared with more than one strip.

The charge sharing and clustering that we implemented worked properly. Hereafter the efficiency of the clustering will be studied, which is not unity as it is observed that some particle hits in Fig. 1 do not have a correponding reconstructed hit, and are optimized by adjusting the ADC threshold.

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Fig. 1. An event display with a simulated event of most-central Au+Au collision. Only one stripixel ladder in the outer layer is shown (x-axis: 36 cm parallel to beam direction, y-axis: 3.43 cm). The **green filled circles** represent particle hit position; the **horizontal and tilted lines** represent x and u stripixels with above threshold energy respectively; the **red open circles and squares** show reconstructed hit position that does and does not have a corresponding particle hit, respectively.

Fig. 2. Position resolution estimated with simulated events of most-central Au+Au collision, i.e. the difference between true and reconstructed hit positions. The **left** and **right** plots are of x and z directions respectively.

Beam test of the PHENIX silicon pixel detector for 120GeV proton

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A Silicon Vertex Tracker (VTX) will be installed for PHENIX experiment at RHIC in 2010. The VTX will enhance the physics capabilities of the PHENIX central arm spectrometers by providing precision measurements of heavy-quark (charm and beauty) production in A+A, p(d)+A and polarized p+p collisions.

The VTX consists of pixel detectors at inner 2 layers (10 ladders [1,310,720 read-out channels] and 20 ladders [2,621,440 read-out channels]) and strip detectors at outer 2 layers (377,856 read-out channels) which cover pseudo-rapidity of $|\eta| \leq 1.2$, azimuth of $\phi \sim 2\pi$. Rikkyo University and RIKEN are responsible for the pixel ladders.

A pixel ladder consists of a stave which supports whole ladder mechanically and four pixel sensor modules[3], two read-out buses[2] as shown in Figure 1. The stave including cooling structure is made from carbon fiber reinforced plastic. The sensor module[3] is made from a pixel sensor, with pixel size of $50\mu m$ in the z (row) direction and $450~\mu m$ in the ϕ (column) direction, and four read-out chips connected by the bump bonding technique. The read-out bus is a copper-aluminum-polyimide base flexible printed circuit board. We established an assembly procedure for a pixel ladder and will start mass production in January 2009.[1] We confirmed the performance of the pixel ladder by using high energy proton beam. In this report, we describe the tracking results of beam test with the pre-production pixel ladders.
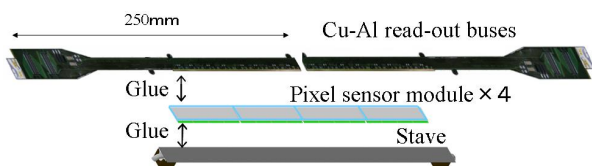
Fig. 1. Structure of a pixel full ladder

In August 2008, a beam test was carried out at Fermi National Accelerator Laboratory in order to check the data taking system (DAQ) and performance of prototype pixel detector. At the meson test beam area, 120GeV proton beam was used. The beam was de-

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livered per 4 seconds. A spill had maximum $\sim 2\times 10^4$ counts.
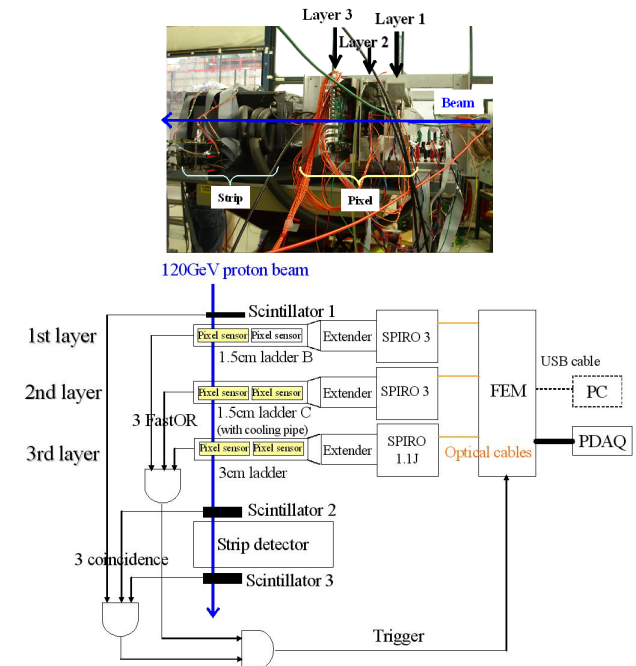
Fig. 2. Setup of beam test. The vertical distance between 1st layer and 2nd layer, 1st layer and 3rd layer were 46.5mm and 86.5mm, respectively.

The setup of beam test is shown in Figure 2. A telescope configuration of three pixel ladders was used. Each pixel ladder was connected to a Silicon Pixel Interface Read Out(SPIRO) board[4]. Three SPIRO boards were fed to a Front End Module(FEM). Three scintillation counters were used as an event trigger and determination of the beam timing. The SPIRO board controls read-out chips and collects data and sends them to the FEM via optical cables. The FEM is a translator between detector specific electronics and PHENIX standard data acquisition modules that sends command signals to the SPIRO board and packs and transmits recieved data. The FEM has a USB interface for downloading the internal configuration from a local PC. Each readout chips has an all-hits-ORed output (FastOR), which will be fired even a single hit in the chip. The trigger is made of a coincidence of FastOR on the three layer and triple coincidence scintillation counter trigger. This system has been operated successfully.

The configuration of the telescope was changed third

time, A, B and C. The difference of the configuration was the position of 2nd layer along column direction.

Geometry	Trigger Rate	Number of Event	3 Hits
A	34	8.9×10^3	3.3×10^3
B	38	6.0×10^3	1.4×10^3
C	36	4.6×10^3	2.6×10^3

Table 1. Run List

DAQ system was able to set several values and take data without out of order. However, trigger rate was low and FastOR trigger has little problem. So Table 1 shows events of "3 Hits" were few, compared with "Number of Event". The "3 Hits" means a number of event which has hits on each three layer.

The track was reconstructed with hit information of each layer by using least-square method after the position alignment in offline analysis. Total of events with hits in three layers was 7.3×10^3 events. A method of the track reconstructed was described in the following.

(1) Mask noisy pixels. Noisy pixel defined that a pixel had more than 15 counts in beam profile of every chip.
(2) Select event which has hit on each three layer. Every one event, draw lines by the least-squares fit methods with conbination of all hits. When χ^2 is at a minimum, the hit positions become true positions in the event.
(3) Get alignment parameters by offline analysis. Before beam test, three layers were aligned manually with a precision on the order of 1mm. A much more precise alignment was performed.
(4) Iterate (1)~(3) until alignment parameters converge.
(5) Obtain residual distribution after applying cut of beam angle. The data within the region of $\sigma = \pm 2$mrad($\sim \pm 0.12°$) in beam angles distribution were used for residual distribution (Figure 3).
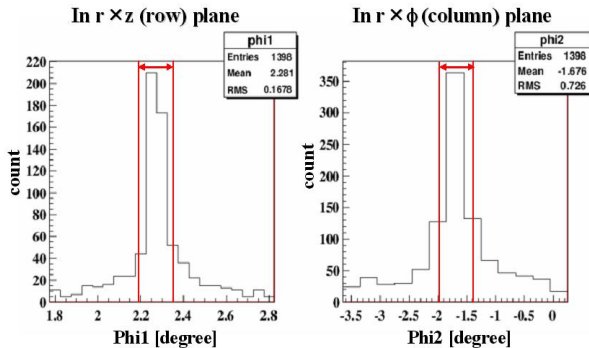
Fig. 3. Projected angular distribution of beam on column-beam (left) and row-beam plane (right). The region surrounded with lines is accepted region.
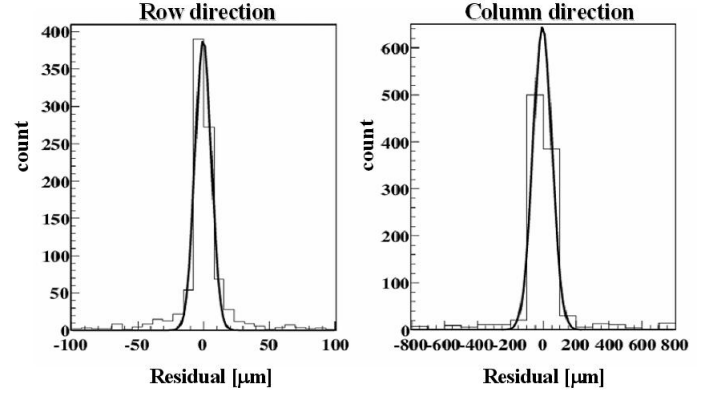
Fig. 4. Residual distributions in row and column directions on 1st layer.

These procedure was performed in every geometry. Finally, three residual distributions were sum up in each layer. The residual distribution in column and row direction on 1st layer are shown in Figure 4. The standard deviations of these residual distributions were calculated to be 6 ± 2 μm and 58 ± 11 μm in the row and column directions, respectively. The position resolution of sensor modules is determined mainly by the two factors. One is the intrinsic position resolution and the other is the effect of multiple scattering in the ladder components. The multiple scattering angle is given by the below equation[5].

$$\theta_0 = \frac{13.6 MeV}{\beta cp} z \sqrt{\frac{X}{X_0}} \left[1 + 0.038 ln(\frac{X}{X_0}) \right] \qquad (1)$$

Here, p, βc, and z are the momentum, velocity, and charge number of the incident particle, and X/X_0 is the thickness of the scattering medium in radiation lengths.

A multiple scattering angle on 1st layer was estimated to be 1.3 μm. The intrinsic resolutions in row and column directions were calculated to be 14 ± 6 μm and 152 ± 30 μm, respectively. The intrinsic resolution depends on pixel size(row : 50 μm and column : 425 μm). We expect the resolution of the pixel sensor module are $50/\sqrt{12} \approx 14$ μm and $425/\sqrt{12} \approx 123$ μmin the row and column directions, respectively.

One thousand clear tracks were measured at beam test. The results of beam test at FNAL show good performance of the pixel detector for PHENIX experiment.

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Performance test of silicon stripixel detector for PHENIX vertex tracker

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A silicon vertex tracker (VTX) for the PHENIX experiment[1] at Brookhaven National Laboratory (BNL) has been developed to enhance physics capabilities[2]. In this article, we report a recent performance test of a stripixel detector for the outer two layers of the VTX.

The stripixel sensor has two-dimensional position sensitivity only with single-sided processing. It consists of $80 \times 1000~\mu m^2$ pixel structures with two interleaved p+ electrodes, and two-dimensional position sensitivity can be achieved by charge sharing between them with a projective readout by strips. One metal strip connects the pixels in a straight line (x read out), while a second strip connects at a 4.6 degree angle (u read out). The stripixel detector has been designed in collaboration with the BNL Instrumental Division[3] and performance of the prototype detector was studied in static electrical tests, beam/source tests and radiation dose tests.[4] The final design of stripixel was determined based on the results. Thickness is 625 μm, for example.

Figure 1 shows the stripixel detector mounted on a prototype readout card (ROC). Signals from the stripixel detector are read out via SVX4 chips[5] which are also mounted on the ROC. The ROC is connected to a prototype ROC control card (RCC) and a front-end module (FEM) compatible with the PHENIX DAQ system.
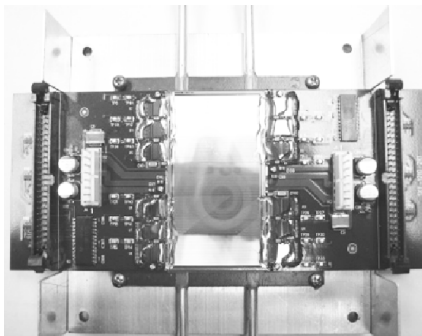
Fig. 1. Photograph of stripixel detector mounted on the ROC.

We tested performance of the whole read out system incorporating the stripixel detector with a beta source

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and 120 GeV proton beam at Fermi National Accelerator Laboratory (FNAL). Important performance characteristics are,

- Signal to noise ratio (S/N)
- Detection efficiency
- Position resolution

In a typical silicon strip detector, detection efficiency is almost 100 %, and position resolution is dominated by the strip pitch. These two characteristics become worse with low S/N.

Performance test with beta source

A beta source test was performed at the chemistry laboratory at BNL. We placed a beta source as close as possible to the stripixel detector, and data was collected by a scintillator trigger making with the detection of penetrated electron. The detector was placed in a dark box with flowing dry nitrogen and zero degree water running in cooling pipes. High voltage was supplied at 200 V.

Figure 2 (top left) shows ADC vs. channels with a beta source. Pedestal subtraction is applied event-by-event, and the pedestal value in each channel is determined by the average of the previous and next four channels. Then the corrected ADC is obtained, as shown in Fig. 2 (top right). We plan to implement this method in the FPGA and conduct zero suppression data collection. A clustering algorithm is used as follows to find a minimum ionization particle (MIP) peak. 1) If the ADC value is above two sigma of the pedestal width, the channel is tagged as hit. 2) If a hit continues to the next channel, they are combined so that the clustered ADC is sum and the clustered channel is calculated by centroid method. 3) A clustered ADC is required to be above 40 to decrease a fake cluster formed by noise. After clustering, we can see a clear MIP peak as shown in Fig. 2 (bottom). The S/N is defined as the most probable value of the MIP peak divided by the average pedestal width. We obtained S/N ratios of 9.3 and 9.7 for x and u, respectively.

Performance test with 120 GeV proton beam

The proton beam was supplied at the Meson Test Beam Facility (MTBF) at FNAL as T984 experiment. A schematic view of the experimental setup is shown in Fig. 3. Three stripixel detectors were placed at 50 mm intervals as a hodoscope in the dark box and supplied
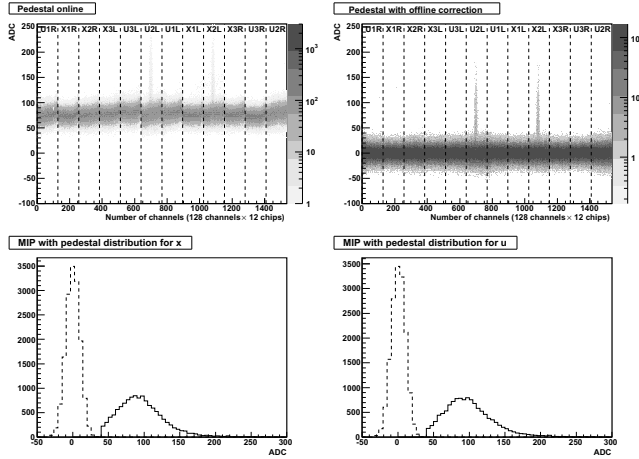
Fig. 2. Results of beta source test. Top) ADC vs. channel (left) and results after correction of pedestal subtraction (right). Bottom) Clustered ADC (solid line) and average pedestal (dotted line) distributions for x (left) and u (right).

with 200 V high voltage via RCC boards. The event trigger was coincidence of three scintillators placed upstream and downstream of the box and the "BEAM ON" signal coming from the accelerator. For analysis, we used the same algorithm as the beta source test and obtained results similar to Fig. 2. S/N ratios of 10.3 and 10.1 were obtained for x and u, respectively. The reason why S/N was higher in the beam test is that we tuned integration timing in the SVX4. We concluded they are consistent.

Figure 4 shows an event structure for one event with linear fit tracks. We can clearly see a penetrating event in raw ADC level and successfully reconstruct proton tracks with this S/N. With this tracking information, the residual distribution, correlated to the position resolution, can be obtained as the difference between the hit position and the expected position which are decided by the track with other two detectors. The residual distribution for the middle sensor in x read out is shown in Fig. 5 (left) and obtained as $0.42 \times 80(\mu m)$ = $33.6(\mu m)$ from the RMS value. The efficiency was determined by looking at the energy deposit in the detector at the expected channel which was also decided by other two detectors. The sum of ADC distribution in the expected channel± 2 is shown in Fig. 5 (right). We extracted the efficiency as $99.5 \pm 0.2\%$ with the hit definition of ADC above 40. Consistent results were obtained for u read out.

In summary, the stripixel detector integrating whole read out system satisfies the required performance with a S/N of about 10. Currently we are preparing for mass production with final feedback aiming for installation in 2010.

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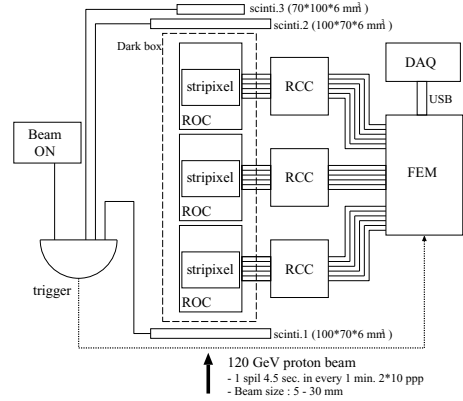
Fig. 3. Schematic view of the T984 setup.
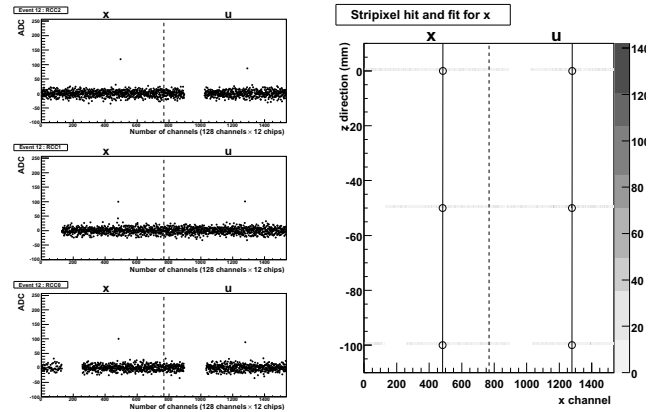
Fig. 4. Event structure for 120 GeV proton beam. Left) ADC vs. channel for all detectors. Right) Position in the beam direction vs. channel. Clustered channel positions are plotted as circle points and tracks by linear fit are shown as straight lines.
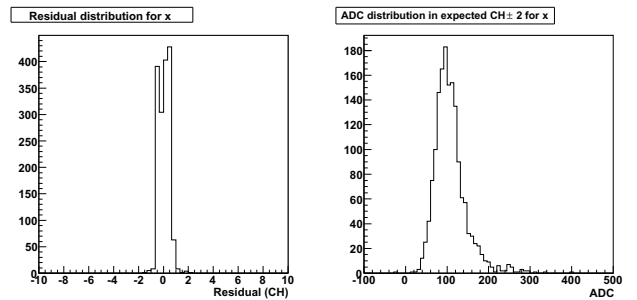
Fig. 5. Left) Residual distribution for the middle sensor. Right) Sum of ADC distribution at the expected channels by tracking. Both are for x.

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High Momentum Trigger Electronics Upgrade of PHENIX Muon Arms for Sea Quark Polarization Measurement at RHIC

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[nucleon spin, W-boson, polarized parton distribution, Electronics, trigger]

Parity-violating production of the W boson with longitudinally polarized protons at RHIC provides a direct measure of the individual polarizations of the quarks and anti-quarks in the colliding protons. The high energy scale set by the W-mass makes it possible to extract quark and anti-quark polarizations from inclusive lepton spin asymmetries in W-production with minimal theoretical uncertainties. Sub-leading twist and higher-order terms in the perturbative QCD expansion are strongly suppressed, and a direct extraction without additional assumptions becomes possible. This program thus will break new ground in our detailed understanding of the proton's structure. The program is initiated by the first operation of RHIC polarized proton beams at its highest operational energy $\sqrt{s} = 500$ GeV starting from 2009.

A new trigger on forward muons in PHENIX identifies and triggers on high momentum muons from W decay suppressing a large number of background low momentum muons coming from hadronic decays. Since the current muon trigger will fire on any muon above 2 GeV/c, it will not provide the required rejection factor for 500 GeV running, which is about 10,000. Two major upgrade projects are parts of this Muon Trigger; 1) Resistive Plate Chambers[1], 2) the muon tracker front-end-electronics (MuTr-FEE) upgrades[2]. This report summarizes the introduction the latter and the installation to PHENIX during 2008 shutdown period.

The MuTr-FEE upgrade features additional fast readouts to the existing MuTr-FEE, which provides momentum sensitivity to the existing muon trigger beyond 2 GeV/c. There are three tracking stations of cathode strip (5mm pitch) chambers in the muon tracker for measuring the trajectory of particles in a magnetic field (with an integrated $B - dl$ of approximately 0.75 Tesla-meters). A new amplifier discriminator (MuTRG-ADTX) board[3] divides the signal into two paths; existing read out path and the digitization path for the fast trigger.

Figure 1 visualizes the principle of the momentum sensitive trigger. The hit signals from three tracking chambers (named station-1, 2, and 3, respectively from the collision point) are immediately digitized and processed by MuTRG-ADTX and are sent to new merger boards (MuTRG-MRG)[4]. The MuTRG-MRG board collects hit signals from multiple MuTRG-ADTXs and formats the data to meet the input format of the Local Level-1 (LL1) trigger module. The LL1 module receives data from MuTRG-MRG and then select the events which have ±1 strip sagitta at station-2 from the linear interpolation between station-1 and station-3 hits, providing the trigger of only high transverse momentum track $P_T > 10$ GeV/c.
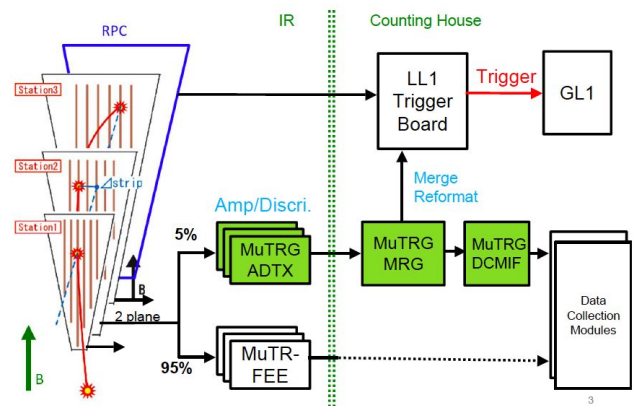
Fig. 1. The concept of momentum sensitive trigger using muon tracker cathode strip readouts.

The R&D, production of these new boards were nearly completed by the end of 2008. 192 MuTRG-ADTX boards were installed to the one of two muon arms in PHENIX and their commissioning starts as soon as Run09 beams are delivered. The installation to the remaining another half of the muon arm acceptance is scheduled during 2009 shutdown period.

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Development of the MuTRG-ADTX boards for the PHENIX muon trigger upgrade

Y. Fukao for the PHENIX MuTr FEE Upgrade Group

The contribution of sea quarks to proton spin is one of the mysteries in the study of the proton spin structure. The PHENIX experiment aims to directly probe the sea quark contribution through measurement of single helicity asymmetry in W boson production. W bosons are measured by detecting high-momentum muons from their decay, using the muon arms in the PHENIX detector.[1] One of the greatest difficulties in measuring a W boson is that the trigger rate would be too high at the designed luminosity to record all events with W candidates. To collect W production events effectively, we are developing a new trigger system, which selects high-momentum muon tracks by performing rough momentum measurement online. An overview of the trigger system is provided elsewhere.[2]

This report describes the development of an amplifier - discriminator - transmitter board (MuTRG-ADTX) for the existing muon tracking chamber (MuTr). Figure 1 is a picture of the MuTRG-ADTX board. MuTRG-ADTX is installed on MuTr and utilizes ∼5 % of the charge induced in MuTr. The remaining 95 % is used by the existing MuTr front-end electronics (MuTr-FEE) for precise offline position measurement. The input charge in MuTRG-ADTX is amplified and discriminated to provide a fast signal for the trigger. The digitized signals from 64 channels are serialized in an FPGA and sent to the downstream data merger board (MuTRG-MRG). Meanwhile, MuTRG-ADTX receives control signals and the beam clock from MuTRG-MRG. Optical fibers are used for the communication between them. Development of MuTRG-MRG is reported elsewhere.[3]

In summer 2007, we installed prototype boards of MuTRG-ADTX to the actual MuTr in the PHENIX detector. They were tested with cosmic rays and sufficient performance was obtained.[4] The prototype was composed of two separate boards – an analog signal part (amplifier + discriminator, AD part) and digital signal part (transmitter, TX part) – due to fears of possible noise from the TX part to the AD part. Based on the knowledge of grounding in the cosmic ray test, the AD and TX parts were combined into one board, MuTRG-ADTX. This modification also provides results in advantages in terms of costs, simplicity and easier installation. The combined MuTRG-ADTX board was again tested at PHENIX during RHIC 2008 run (Run08) and we confirmed that performance of MuTRG-ADTX was consistent with the prototype.

After a few minor modifications based on results of the test experiment, we started mass production of
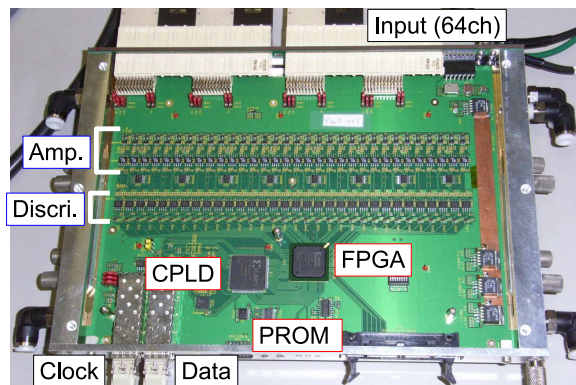
Fig. 1. MuTRG-ADTX.

MuTRG-ADTX. A total of 220 boards were produced in 2008. The boards were carefully examined before installation to the MuTr because access to MuTRG-ADTX is extremely difficult after installation. Check items for MuTRG-ADTX were : (1) signal reconstruction and efficiency, (2) fake hit rate to evaluate noise level, (3) cross talk between channels, (4) various slow controls including operation mode selection and threshold setting for the discriminator, (5) turn on curve of the trigger efficiency for each channel, (6) remote update of FPGA. In addition, noise increase and gain reduction on MuTr-FEE were checked for each MuTRG-ADTX board at the test bench. Finally, all produced boards passed the examination.

By the end of 2008, MuTRG-ADTX boards were installed for the north muon arm as scheduled, together with necessary infrastructure such as the low voltage power supply, cooling water system and optical signal lines between the beam interaction region and counting room. Tests of signal readout and slow controls were carried out for all installed MuTRG-ADTX boards, and we confirmed that the boards were fully operational. The impact of MuTRG-ADTX installation on MuTr-FEE, noise and gain, was measured and the effects were reasonable.

We plan to collect data on the new W trigger and evaluate its performance during the polarized proton run with $\sqrt{s} = 500$ GeV in 2009 (Run09). Installation into the south muon arm is scheduled for summer 2009.

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3) I. Mibe et al.: RIKEN Accel. Prog. Rep. **42** (2009).
4) Y. Fukao et al.: RIKEN Accel. Prog. Rep. **41** (2008).

Development and evaluation of the MuTRG-MRG and DCMIF boards for the PHENIX muon trigger upgrade

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The parity violating single-spin asymmetry A_L of muons from the W decay in the 500 GeV polarized proton-proton collisions will be measured at the PHENIX in the future running. The PHENIX Muon Tracker Front End Electronics (MuTr FEE) needs to be upgraded to introduce momentum-sensitivity to the muon trigger by the fast measurement of the saggita (a displacement of track position due to the magnetic field in three MuTr stations)[1)].

In this report, development and evaluation of two key components of the trigger system, i.e. data merger board (MuTRG-MRG) and interface board to data-collection-module (MuTRG-DCMIF), are described.

The primary function of the MuTRG-MRG board is to receive data from the Amplifier-Discriminator-Transmission board (MuTRG-ADTX)[2)] boards and send reformatted data to the Local Level-1 Trigger board (LL1). The MuTRG-DCMIF board samples the merged data recorded in the MuTRG-MRG board, and send it to the Data Collection Module (DCM), a read-out port of the PHENIX data acquisition system, for the monitoring and diagnosis of the system. The requirements and specifications of the MuTRG-MRG and DCMIF boards are described elsewhere[3)].

Prototype boards of the MuTRG-MRG and DCMIF boards were developed. They have optical transceivers with 16-bit serial links, 24-bit LVDS serial links, and VME J1 interfaces. The Xilinx Spartan3 FPGA is used to process the incoming data. The board power (3.3 V) is supplied through the VME64X backplane. Size of these boards is 9 U in height and 160 mm in depth with 10 layers (Fig. 1). These boards are installed in custom-made VME sub-racks in the PHENIX rack room. Each VME sub-rack accommodates sixteen MuTRG-MRG boards and two DCMIF boards. A full-size rack and its service for the VME sub-racks and optical patch panels have been installed in the PHENIX rack room.

Data communications as well as propagations of control signals have been individually tested at PHENIX under conditions as realistic as reasonably achievable during the RHIC machine shutdown in 2008. One of major test milestones was a successful data transmission from the MuTr cathode strip to the DCM with a full chain of the MuTRG electronics (MuTRG-ADTX,
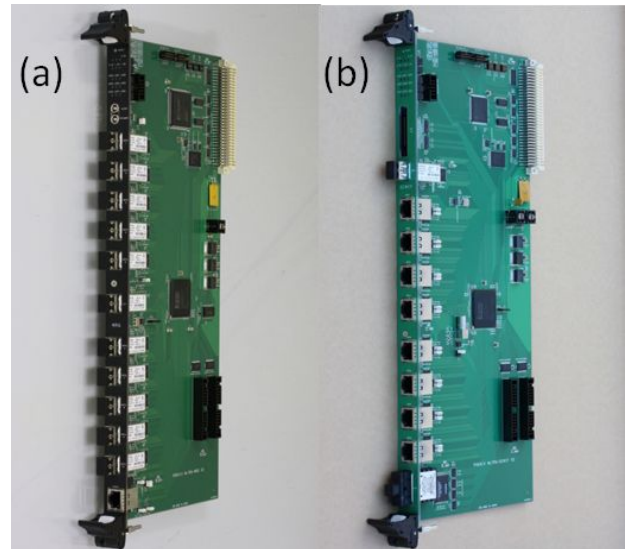
Fig. 1. (a) MuTRG-MRG board, (b) MuTRG-DCMIF board.

MRG, DCMIF) and the PHENIX standalone data acquisition system, including event building with existing MuTr subsystem.

The consistency of schedule and technical details for integration has been discussed by the internal PHENIX review committee. Upon positive feedbacks from the review, the boards production was started. In total 70 MuTRG-MRG boards and 12 MuTRG-DCMIF boards were produced. These board will be installed to PHENIX after quality assurance check-ups.

In summary, the prototypes of MuTRG-MRG and DCMIF boards have been developed. All individual functions of these boards were evaluated at PHENIX. With these boards, the MuTRG electronics were integrated to the PHENIX data acquisition system. Details of these achievements are described in the master's thesis[4)].

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A fast, momentum sensitive muon Trigger for PHENIX using resistive plate counters[†]

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[Spin Physics,PHENIX,Trigger]

The parity violation of the weak interaction can be used to directly access the quark and sea quark helicities of the nucleon[1]. Colliding longitudinally polarized protons at RHIC energies of $\sqrt{s} = 500$ GeV one can produce real W bosons which will be detected through their charged decay lepton. The high mass of the W-boson makes it possible to isolate these decay leptons at high transverse momenta in the central and muon arms of the PHENIX detector. The existing muon trigger selects particles which pass through the muon arms including several layers of absorbing material. Presently, the muon yield is dominated by low momentum muons from hadron decays. At the expected luminosities for 500 GeV collisions at RHIC, the decay muon rate will far exceed the available bandwidth for data acquisition in Phenix. Figure 1 shows that a momentum sensitive first level trigger would be well suited to reject low momentum muons. For this purpose two detector upgrades are underway to create a momentum sensitive first level trigger which selects only high momentum muons. The first project is an upgrade of the front end electronics of the existing muon tracking stations to promptly feed muon tracking information to the trigger processor[2]. The second detector upgrade adds two layers of resistive plate counters (RPC) before and after the muon tracking system. The RPCs will be the only detectors with fast time response in the PHENIX muon spectrometers. The RPC can tag straight high momentum muon tracks in the first level trigger. The RPC timing will be critical in rejecting beam related backgrounds (prompt and thermal neutrons) in the trigger and backgrounds from cosmic ray muons in the offline analysis. Finally the timing information from the RPCs will be necessary to correlate W-candidates with the correct beam polarization information. The PHENIX muon trigger RPCs consist of double gas gaps sandwiching a signal plane with pick-up electrodes. The gas gaps are formed with bakelite plates, 2mm apart and externally coated with a thin layer of graphite for charge distribution. In order to keep the two plates at a constant distance (and thus at a constant electric field) polycarbonate spacers are located through the gap (see Fig. 2). The gas applied consists of 95% Freon, 4.5 % Isobutane and 0.5% SF_6. The applied voltage is between 8.5 and 9.5 kV. The readout plane between the two gas gaps consists of large area printed circuit boards with copper strips. If a charged particle is traversing the gas volume an avalanche is created by the ionization. The amplification of the charge in the high electric field induces a detectable mirror charge on the pads outside the gas and electric field volume. The signal charge has a large dynamic range from 20 fC to 20 pC. The signal is being discriminated in front end electronics custom developed in CMS and are sent to TDCs.

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[*2] RIKEN BNL Research Center, USA
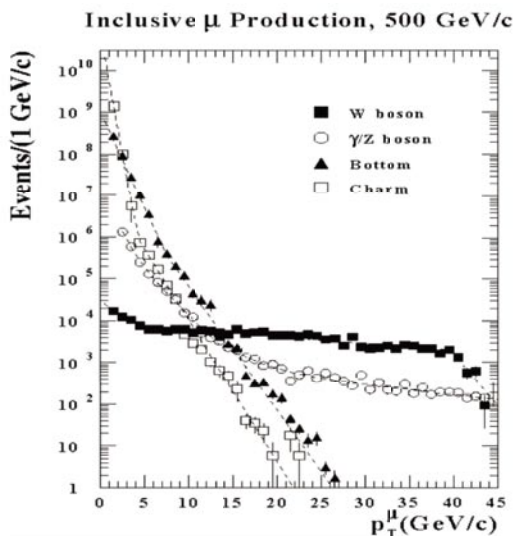
Fig. 1. Muon yields for different processes as a function of the transverse momentum of the muon.
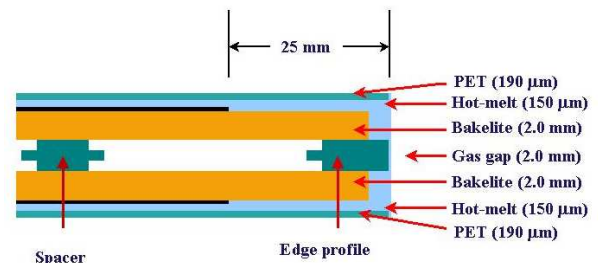
Fig. 2. Schematic view of a RPC gap showing two sheets of bakelite, the polycarbonate spacers, the are covered with graphite and the edge of such a gas gap.

1 Detector design

In order to obtain the maximum possible active area and to have a better matching with the existing muon tracking system the modules will be staggered in z in order to overlap inefficient areas in one detector module with an active area in the adjacent module. Two sets of detectors are being built. The first detector (RPC1) will be located downstream of the central magnet yoke just in front of Muon Tracker station 1. In order to maximize the acceptance in this detector octants will be staggered in azimuth around the beam axis to obtain full azimuthal coverage. The polar angle coverage is constraint by the PHENIX central magnet yoke and the in-sensitive boundaries of the RPC gas gaps. The resulting acceptance is only slightly less than the acceptance of the existing muon tracking system. The segmentation of the RPCs is between 200 and 480 pseudoradial strips over the full azimuthal angle and 4 segments in the polar angle. Upstream of RPC1 an additional 10-16cm thick lead absorber is planned which further increases the trigger rejection and reduces offline backgrounds to the W measurements (see[3]). The second detector (RPC3) will be located behind the last muon ID steel absorbers at the intersection of the Experimental area and the RHIC accelerator tunnel.For the RPC3 detector station the inactive regions in the azimuthal direction coincide well with the size of the existing inactive regions in the PHENIX muon systems. For this reason the detector design focused on obtaining the optimum coverage along the polar angle direction. The RPC 3 detector stations will be formed from 16 half octants where each half octant will contain three detector modules. This configuration was driven given the maximum dimensions of gas gaps available from the gap production facility at Korea University. A sideview of the RPC detector locations can be seen in Fig. 3

2 Detector production

The production of the RPC detectors is organized around international cooperation within several PHENIX institutions and utilizing existing RPC technology from the CMS forward muon trigger detectors. Bakelite plates have been obtained from the CMS vendor in Italy. The plates were cut and cleaned in Italy and then shipped to Korea. From the raw bakelite plates the graphite coated gas gaps are being manufactured at Korea University. The module frames and the the readout strips are produced in China under the supervision of the CIAE group in PHENIX. Both, module frames and gaps are shipped to BNL where they are tested and assembled into modules. The support structure will be build by an US manufacturer, test-assembled at UIUC before insertion of the modules at BNL and subsequent installation in the experiment. At all steps in the production chain the quality of the produced gaps will be closely monitored through leakage current measurements, efficiency measurements and environmental controls. The readout electronics has been developed at Nevis and is presently being produced. Fast custom trigger processors are being developed at Iowa State University.
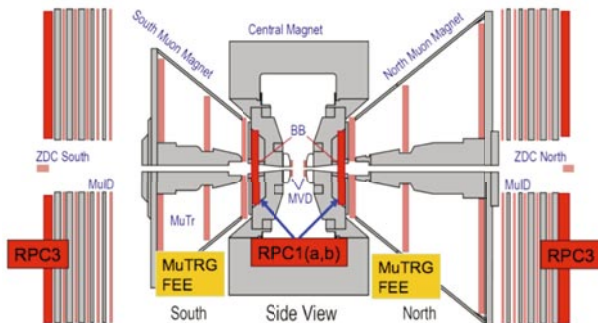
3 Integration and Schedule

Two RPC prototypes that are close in dimension and design to the final RPC3 half octants have been installed in PHENIX and will be tested during run 9. The mass production of the final detector has been started in December 2008. As the RPC 3 detectors are sitting behind the muon identifier they have to be installed from the RHIC tunnel which requires technical support from the Collider Accelerator department of BNL. All services for RPC3 will be provided from the accelerator tunnel. The installation of the first RPC3 detector stations is planned for the summer of 2009. The station will be added to the PHENIX muon spectrometer north which already has been outfitted with new trigger electronics for the muon tracking chambers. The installation of the south side of RPC 3 will follow in 2010. The two smaller detector stations, RPC1, also will be installed in the summer of 2010. Subsequently, the full high momentum muon trigger will be available in PHENIX for run 11 when the first high luminosity polarized proton run at a center of mass energy of 500 GeV is anticipated.

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Fig. 3. Sideview of the PHENIX detector including the schematic locations of RPC stations 1 and 3.

DAQ system Upgrade for optical alignment system of PHENIX Muon Tracker

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One of the major goals of the physics in the spin program at the RHIC-PHENIX experiment is to investigate the spin polarization of valence and sea quark (Δu, Δd) [1] in a proton separately by measuring W boson production asymmetry in the polarized proton-proton collision at the center of mass energy 500GeV.

The W boson is produced by collision of u and anti-d or d and anti-u and can be used for flavor decomposition of protons. The single spin asymmetry of the W production is shown as follows.

$$A_L^{pp \to W^+ X} = \frac{\Delta u(x_1)\overline{d}(x_2) - \Delta \overline{d}(x_1)u(x_2)}{u(x_1)\overline{d}(x_2) + \overline{d}(x_1)u(x_2)} \quad (1)$$

$$A_L^{pp \to W^- X} = \frac{\Delta d(x_1)\overline{u}(x_2) - \Delta \overline{u}(x_1)d(x_2)}{d(x_1)\overline{u}(x_2) + \overline{u}(x_1)d(x_2)} \quad (2)$$

In the case of $x_2 \ll x_1$, the equations of (1) and (2) can get into $\Delta u/u$ and $\Delta d/d$. In the case of $x_2 \gg x_1$, those equations can get into $\Delta \overline{d}/\overline{d}$ and $\Delta \overline{u}/\overline{u}$.

$$A_L = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \quad (3)$$

In the equation (3), σ_- is a cross-section in the collision between un-polarized and polarized protons with plus helicity. σ_+ is that with minus helicity. Since both beams are polarized at the RHIC, one of two beams will be treated as un-polarized by taking the sum of positive and negative helicities. In this way, A_L can be evaluated for each beam simultaneously from a given collision. According to deep Inelastic Scattering experiment, the un-polarized distribution function of each quarks, u(x), d(x), $\overline{d}$(x) and $\overline{u}$(x) uis reasonably well measured. Thus precision measurement of polarized distributions e.g. Δu, Δd, $\Delta \overline{u}$ and $\Delta \overline{d}$ are desired. They can be achieved via the W boson asymmetry measurement at RHIC. The W boson measurement is actually carried out by detecting muons' decay whose branching ratio is 10%. The muons from W decay have typically high momentum (transverse momentum P_t of 20GeV/c) due to heavy mass of W is 80GeV/c^2 and will be distinguished from dominant low momentum backgrounds.

A muon arm of the PHENIX consists of the Muon Identifier (MuID) and the Muon Tracker (MuTr). The MuID is designed to identify muons from hadron backgrounds using muons' penetration power through thick absorbers. The MuTr is for measuring momentums.

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Three stations of cathode-strip readout tracking chambers are mounted inside conical-shaped muon magnets. These stations are called "station-1", "station-2" and "station-3" starting from the near side of the collision point. Each station is symmetrically segmented into octants in azimuthal orientation. Each station is made of 2 or 3 gaps. An anode wire plane sandwiched by cathode signal planes forms a signal gap. The MuTr cambers are designed to provide a position resolution of 100–300μm, however this designed resolution has not been achieved with real data. The reason will be discussed in this report. An illustration of the MuTr is shown in Fig.1.
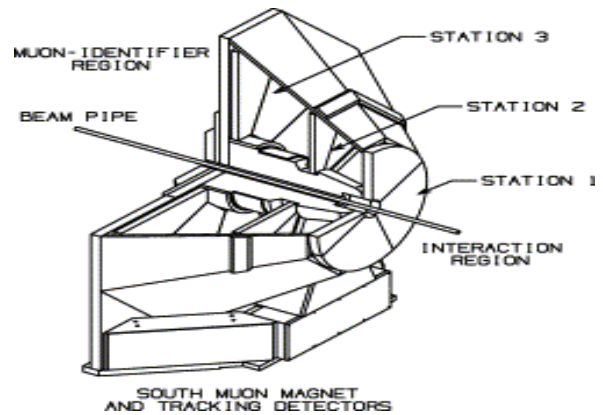
Fig.1: The illustration of the MuTr

A muon which enters into the MuTr is kicked toward the azimuthal direction by the radial direction magnetic field. We measure the momentum of a muon by using sagitta which is the deviation of a hit in station 2 from the straight line between hits in the station 1 and 3. The momentum of the muon is inversely proportional to the sagitta.

The muon from the W boson has higher momentum and its sagitta at the MuTr is quite small. The spectrum of single muon background drops sharply with its momentum, therefore the momentum resolution will affect the signal-to-noise ratio for the W asymmetry measurement.

However, each station moves 100-300μm because of the temperature excursion and the magnetic field. As a result, these displacements become one of the causes of the observed resolution which is 50-200% worse than the designed one.

The Optical Alignment System (OASys) [2] measures the relative position movements among stations. There is a light source at the station-1, a lens at the station-2, and a CCD camera at the station-3. An image on the CCD camera reflects the relative movement among stations. Each octant, which covers 1/8 of each arm, has 7 sets of these as in Fig.2.
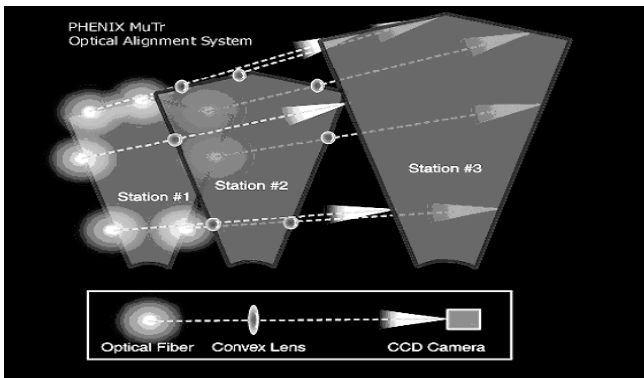
Fig.2: The image of Optical Alignment System (OASys)

OASys can track the relative movement among stations with accuracy of $25\mu m$[3]. They can correct these positions and improve momentum resolution as a result

The Data Acquisition (DAQ) system of OASys consists of 112 CCD cameras, 2 multiplexers, 2 GPIB-Ethernet interfaces, 2 optical fibers, 2 pairs of fiber transmitter and receiver, an image capture board and a DAQ PC. The DAQ PC sends GPIB commands to the multiplexer via the Ethernet and the multiplexer selects the camera to capture the image. The video capture board obtains the spot image data from the selected camera, via an optical fiber to cut ground loop. The CCD camera transmits 768×498 pixel. The video capture board, however, can receive 640×480 pixel images. One longitudinal pixel corresponds to $11\mu m$ and one lateral pixel corresponds to $13\mu m$. The diagram of the new DAQ system which was developed in 2008 is shown in Fig. 3.
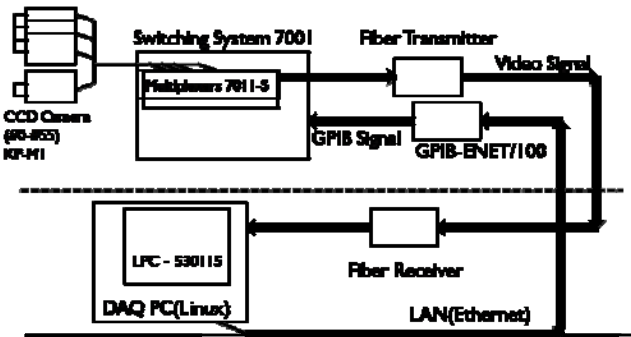
Fig. 3: Diagram of new DAQ system.

The previous DAQ system[4] used two DAQ PCs which ran under Microsoft Windows operating system, National Instruments Labview and one analysis/storage Linux PC. The digitized images were previously transferred to the analysis PC via the network. However, this network service was terminated after a change in the network security policy in BNL.

The new DAQ system uses only one PC to collect data and to store the captured images. We employed the combination of a Linux operating system and a gcc compiler which is known to be very stable. As a consequence the new DAQ has been performing much more stably than the old one and is free of the data transfer problem. In addition, it makes remote maintenance so simple.

In addition to the system change, a configuration file has been introduced for the system control. Some captured images on CCD cameras are obscure due to misalignment of the lens. However, the center positions of such images can be sharpened by integrated images. Due to the weak contrast images, captured images from the same camera are integrated in a digital fashion. The numbers to be integrated in digital images can easily be customized via the newly introduced configuration file.

The new DAQ system was commissioned during the OASys maintenance through the summer shut down period after Run08. In this maintenance period, major repair work was carried out for first time after several years since installation. One broken light source has been fixed, and many camera positions have been re-aligned. As a result, the number of available cameras increased from 30 to 98 out of a total 112.

A typical acquired image from the new system is shown in Fig.4. The spot of the image can authentically be recognized.
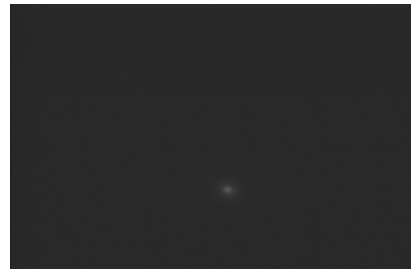
Fig. 4: An image on a CCD camera with the new DAQ system

The projection and fitted images should be prepared as the next step to extract the center position of spot image. An example which uses the image of Fig.4 is shown in Fig.5. The new DAQ system of OASys has been running stably from January 2009. It is expected to improve momentum resolution of the MuTr in coming 500GeV polarized proton run from March 2009.
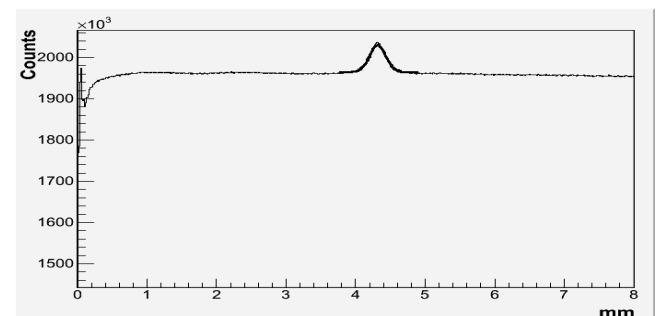
Fig.5. The projection and fitted image on X axis.

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CCJ Operation in 2007-2008

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1 Overview

The operation of CCJ[1,2], RIKEN Computing Center in Japan for the RHIC[3] physics, started in June 2000 as the largest off-site computing center for the PHENIX[4] experiment at RHIC. CCJ was initially planned to perform three roles in PHENIX computing, 1) as the simulation center, 2) as the Asian regional center and 3) as the center of spin physics. Recently, DST (Data Summary Tape) production from raw data has become more important, especially for the p+p data. Out of the many off-site computing facilities of PHENIX, only CCJ can handle the several hundreds of TB of raw data in use of HPSS (High Performance Storage System)[5] for the time being.

A joint operation with RSCC (RIKEN Super Combined Cluster System)[6] was started in March 2004. Most of our computing power is now provided by RSCC. On the other hand, the disk storage and service nodes are still located at the CCJ machine room in RIKEN Main Building and maintained by ourselves. Renewal of RSCC is on going and new CPUs will be available in August 2009.

Many analysis and simulation projects are being carried out at CCJ. They are shown on the web page: http://ccjsun.riken.go.jp/ccj/proposals/.

2 Current configuration

2.1 PC nodes

In June 2008, 112 PC nodes, which were purchased in 1999–2001, were retired and discarded. After that, we have approximately 80 PC nodes operated using Linux in the CCJ machine room. In these nodes, 54 nodes are used for calculation and the others are used for various services, e.g., data transfer, monitoring of nodes and network performances, database servers, log-in servers, WWW and mail server, and so on. Each calculation node has 1 GB of memory, 2 GB of swap area, 10–31 GB of local disks and dual CPUs (Pentium III 1.4 GHz and Pentium 4 2.0 GHz). Scientific Linux (SL) 4.4 is operated on the calculation nodes similarly to at RCF (RHIC Computing Facility)[7], which is the main analysis facility for PHENIX. At CCJ, upgrade from SL 3.0.5 was performed in April 2008.

Out of the calculation nodes, 36 nodes were augmented with 300 GB of local disk in March 2006, on which 10 TB of nDST (nano-DST) data are located in order to avoid the overhead of the data transfer from the data servers or HPSS. This "Data in local disk"

scheme is used by users with applause. These nodes were so old – purchased in March 2002 – that 14 times of system-disk crash occurred in 2008. The second-hand SCSI disks recycled from the retired servers and RAIDs were used for repairing.

Each RSCC calculation node has 2 GB of memory, 100 GB of local disk space and two Xeon 3.06 GHz processors. Out of the 1024 calculation nodes in RSCC, 128 nodes were dedicated to CCJ usage. In August 2008, the dedicated node was reduced to 64 because the congestion of the entire CPUs in RSCC. The dedicated nodes share the PHENIX software environment and can access the CCJ data servers as well as the nodes in the CCJ machine room. In order to run the PHENIX software, the operating system should be same as PHENIX, namely, SL 4.4 at present. This is why we need the 'dedicated nodes', in other words, we cannot share the CPU with the another RSCC users.

On the calculation nodes, the batch queuing system LSF[8] is operated. Version 7.0 is used in CCJ, and 6.2 is used in the CCJ-dedicated nodes in RSCC.

Six temperature monitors were deployed in September 2008 and monitored by WEB using Cacti[9] graphical tool, which was newly installed in 2008 and is also used to visualize the LSF performance and so on.

In February 2009, following success of the "Data on local disk" scheme, 18 nodes of new PC servers (HP ProLiant DL180 G5) were delivered. Each node has dual CPU (Quad–Core Xeon 2.66 GHz), two 146 GB SAS disks for the system, eight 1 TB SATA disks for the data storage, and 16 GB of memory. I/O bound jobs like the nDST analysis will be performed in the servers.

2.2 Data servers

We had a main server (SUN Fire V880) using Solaris 8 for the NIS/DNS/NTP servers and the NFS server for the users' home region on the 8 TB RAID. This machine was replaced by a new server machine, SUN Enterprise M4000 using Solaris 10 with the 10.5 TB of FC-RAID. The DNS, NIS, and NTP/NFS servers were replaced by the new machine in June 2008, October 2008, and January 2009, respectively. The home region is formatted by VxFS[10] and served by NFS v3. The old server and RAID were discarded in Feb. 2009.

We have five data servers (SUN Fire V40z), which are operated by SL4. They serve five SATA-RAID systems (45 TB) and three FC-RAID systems (26 TB) which are formatted using XFS[11]. In order to keep the total I/O throughput, *rcp* command is used to read the data on these servers instead of NFS.[2]

In 2008, frequency of the hang-up of V40z servers

was very low unlike the previous year.

2.3 HPSS

HPSS version 6.2 is used as a mass-storage system at CCJ and RSCC. As the first step of the renewal of RSCC, tape robots and HPSS servers were renewed in November 2008. A new robot and servers are located on CCJ machine room, instead of the RIKEN IT Building where the old system was located. Three UPSs (10.5 KVA each), additional power line and additional air-conditioning system for the robot and servers were newly equipped.

For the new HPSS core server and disk/tape movers, seven IBM p570 servers are operated using AIX 5.3. Twelve (six for CCJ) LTO-4 drives (120 MB/s I/O with 800 GB/cartridge), which are connected six (three for CCJ) tape movers, and 5000 LTO tapes (3000 for CCJ) are installed in the tape robot IBM TS3500, which can handle up to 10275 LTO tapes in current configuration. Since the old tapes cannot be used in the new tape drives, copying the data to the new tapes in the new robot was started in December 2008. Copying approximately 1.34 PB (2.02 M files) of CCJ data stored as of 1 January 2009 will be completed until the end of April 2009.

3 PHENIX software environment

Two AFS[12] clients are operated using OpenAFS on Linux to share the software environment of the PHENIX experiment as analysis and simulation libraries, configuration files and so on. The total data size copied by AFS daily or weekly from BNL is approximately 330 GB as of January 2008. All the calculation nodes are served the software by NFS, not by AFS. Using a *rsync* server, the PHENIX software environment are also shared by PHENIX collaborators in Japan.

Three PostgreSQL servers are operated for the calibration database of PHENIX. The data size is approximately 60 GB as of January 2008. The data is copied daily from BNL.

4 WAN, data transfer and DST production

The SINET3 (maintained by NII[13]) connects RIKEN Wako Campus to the Internet with 10 Gbps of bandwidth. Originally, two aggregated 1000BASE lines connected CCJ main switch (Catalyst 4506) and RIKEN Firewall with only 1.5 Gbps of bandwidth. For the data transfer between BNL, dedicated 10GBASE switch (Foundry FESX424) was deployed in CCJ and connected to RIKEN Main switch by a 10GBASE line in November 2007. Also for the transfer, dedicated four PC servers (HP ProLiant DL145 G3) which are operated by SL5 with a Grid environment (VDT[14] 1.8.1) were deployed. Each server has two 1000BASE

network I/F, one is connected to the Foundry, and the other is connected to the Catalyst. The data from the BNL are transferred through the former line, and are written to the CCJ-HPSS through the latter line. Using the setup, a 360 MB/sec transfer rate from BNL to CCJ was achieved in the test.

In the PHENIX Run-8 (November 2007–March 2008), approximately 100 TB of p+p data were transferred using the data-transfer machines in February–March 2008. The data were sent from the PHENIX counting house in the 'semi-online' manner, namely, before they stored in RCF-HPSS, to avoid an overhead to read from the tape. As a sustained rate for a day, approximately 100 MB/s (8 TB/day) was achieved using gridFtp[15]. Another 10–20 TB were also sent after the Run period. Thus the amount of Run-8 raw data stored in CCJ-HPSS is 117 TB in total. DST production was conducted mainly in August–October 2008 with the reduced 64 nodes in RSCC and 21 TB of analyzed data (nDST) were produced out of 117 TB of raw data, and sent to RCF.

5 Outlook

In 2009, one of the main task of CCJ is the data transfer of PHENIX run9 p+p raw data, which are expected to be 200-500 TB in the Run started January 2009. The DST production using the raw data is another task. To process such large amount of data, joint operation with the renewed RSCC after August 2009 is important.

Main network switch will be replaced in July 2009 by Catalyst 4900M, which have eight 10GBASE ports. Using this switch, a 10GBASE connection between CCJ and HPSS/renewed RSCC will be established.

The condor batch queuing system[16], which is already used in RCF, should be tested in the new PC servers. When it works well, LSF will be replaced.

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III. RESEARCH ACTIVITIES II

(Material Science and Biology)

1. Atomic and Solid State Physics(ions)

Microdose damage observed in power MOSFETs with trench structures

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Ther power MOSFET is a frequentaly used device in power supply systems. Recently, a new type of power MOSFET with trench gate structures, shown in Fig. 1, has be come available for commercial use. The vertical and straight current path in the trench gate structure makes it possible to decrease the size of a unit cell and increase the number of cells in a MOSFET chip, and this helps lower on-resistance and increase the efficiency of the power supply system.
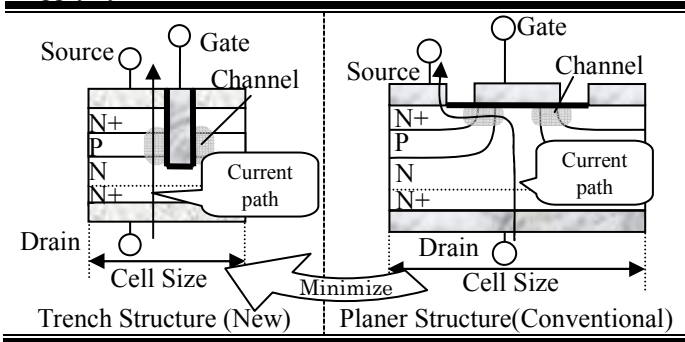
Fig. 1. Cross-section of power MOSFET structures.

However, it has been reported that the trench structure shows anomalously large degradation of electrical properties due to heavy ion irradiation.[1] This degradation could have serious consequences in space systems, and thus therefore the heavy ion irradiation was performed using a cyclotron at RIKEN to investigate the criticality of the degradation. Kr ions were used, and their energy, LET, and range in Si were 5.5 GeV, 11 MeV-cm^2/mg and 1.26 mm respectively.

The mechanism is a microdose effect, i.e., an extremely localized dose effect. As shown in Fig. 2, a heavy ion running through the gate oxide parallel to the channel makes an ion track parallel to the channel. This track induces a leak current path and the increase in leak current decreases threshold gate voltage (=ΔV_{TH}). This degradation
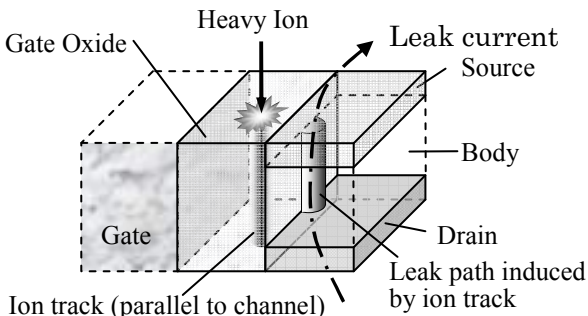
Fig. 2. Microdose effect

will cause a number problem for spacecrafts (e.g., switching failure).

We observed the incident angle dependence of ΔV_{TH}. Fig. 3 shows the result.
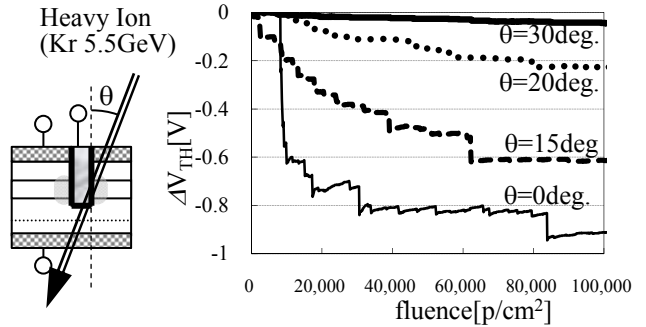
Fig. 3. Incident angle dependence of ΔV_{TH}.

As the incident angle increases, ΔV_{TH} decreases. Only extremely small V_{TH} shifting was observed over 30 degrees. These data show ΔV_{TH} step down shifting events. The measured cross section of the degradation event is 2.0×10^{-3} [cm^2].

LET>1.0 [MeV/(mg/cm2)] particle flux was calculated with CREME96 code assuming altitude, inclination and geomagnetic condition of 700 km, 98.6 degrees and stormy, respectively. The result was 5.4×10^{-1} [p/m^2/s/str]. The event rate in orbit was calculated using Eq.1. The critical angle is assumed to be 30 degrees utilizing Fig. 3, and the effective solid angle is $2\pi\{1-\cos(30[\deg.])\}$.

$$\left(5.4 \times 10^{-1} \left[p / m^2 / s / str\right]\right) \times \left(2 \times 10^{-7} \left[m^2\right]\right) \times 2\pi \left(1 - \cos\left(30[\deg.]\right)\right)$$
$$= 9.1 \times 10^{-8} \left[events / s\right] \quad (Eq.1)$$

This result means the event rate is about 130 day/event. Additionally, Fig. 3 shows that there is recovery from the microdose effect is due to the annealing effect in a few minutes. We can predict that the degradation events in trench structure will not be critical for space applications. Our next study will be an estimation of criticality, strictly for space use.

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Structure of ePTFE irradiated with a 5 MeV/nucleon 14N beam

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Amperometric gas sensors have been widely used in industrial applications and environmental monitoring for detecting hydrogen, hydrogen sulfide, nitrogen oxides, and other gases.[1,2] However, superior sensitivity and selectivity of the sensor is a constant requirement. In this study, we tried to use ion beam irradiation of expanded polytetrafluoroethylene (ePTFE) membranes to improve gas permeability characteristics of the sensor electrode. We expect ion beam irradiation of the membrane to influence the permeability of gases, wettability of the membrane/electrolyte interface, and electrochemical reaction properties of gases at the gas/electrode/membrane interface.[3,4] At first, surface analyses were performed to investigate mechanisms underlying the effects of ion beam irradiation on modification of ePTFE. The ePTFE membranes (Sumitomo Denkou, Japan) used had 0.3 μm pore size, 34% porosity, and 0.2 mm thickness. The membranes were 30 mm square and were irradiated with 5 MeV/nucleon N^{7+} ions from the AVF cyclotron with fluences from 1×10^{12} to 3×10^{13} ions/cm^2 at room temperature.

Ion beam irradiated and non-irradiated ePTFE were coated with gold in a plasma coater (SG-701, Sanyu Denshi, Japan). Microphotographs of field emission scanning electron microscopy (SEM) were obtained at a 5 kV acceleration voltage (JED6330F, JEOL, Japan). Figure 1 shows the SEM images of the non-irradiated ePTFE and the ion-irradiated ePTFE membrane with a fluence of 3×10^{13} ions/cm^2. The non-irradiated ePTFE has a micro porous structure consisting of nodes and fibrils of PTFE. The pore size of the ion-irradiated surface increased and the shape of the surface was more complicated compared to the non-irradiated ePTFE membrane.
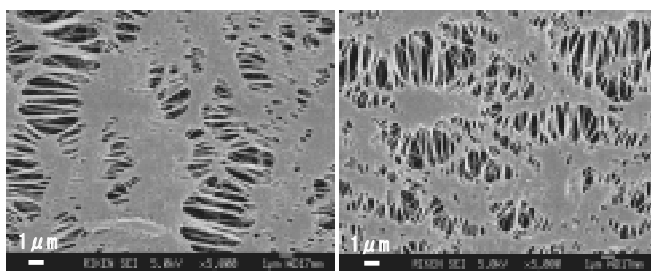
Fig. 1. SEM images of non-irradiated ePTFE (left) and ion-irradiated ePTFE membrane with a fluence of 3×10^{13} ions/cm^2 (right).

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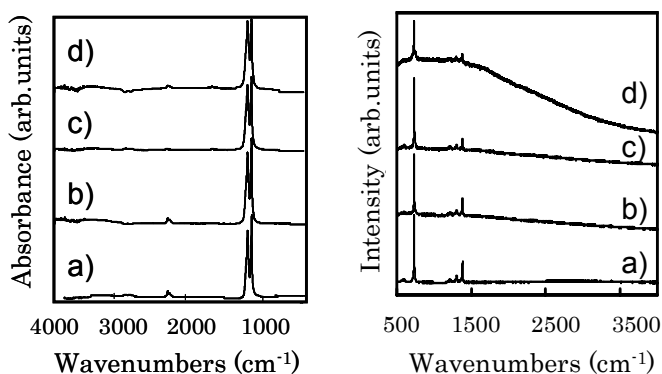
Fig. 2. IR (left) and Raman spectra (right) of non-irradiated (a) and ion beam irradiated ePTFE with fluences of 1×10^{12} (b), 1×10^{13} (c), and 3×10^{13} ions/cm^2 (d).

The structures of ion beam irradiated layers were investigated using Fourier transform infrared spectroscopy (Nexus 470, Thermo Nicolet, USA) combined with attenuated total reflectance (FT-IR-ATR). In this analysis, the incident angle of light emitted from KBR on the specimens was 45°. The spectral range 400-4000 cm^{-1} was analyzed and investigated by means of Raman spectroscopy (LABRAM, Jobin Yvon) with a 632.817 nm He-Ne laser. Figure 2 shows the IR spectra and Raman spectra of non-irradiated and N-ion beam irradiated ePTFE with fluences of 1×10^{12}, 1×10^{13}, and 3×10^{13} ions/cm^2.

In the IR spectra, characteristic peaks are observed at 1150 cm^{-1} and 1205 cm^{-1} which are assigned as C-F bond. The absorbance peak of C-F was depressed with increased fluence of N-ions. The results of Raman spectroscopy at fluence of 3×10^{13} ions/cm^2 shows a broad hump at 1300-1600 cm^{-1} which corresponds to the formation of amorphous carbon. The characteristic peaks of CF$_2$ (735 cm^{-1}) and C-C (1384 cm^{-1}) also decreased with increased fluence. In the ePTFE, the changes in internodal distance, density between nodes and the C-C radical were induced by 5 MeV/nucleon N-ion irradiation. We plan to study gas sensing properties of sensors using the ion-irradiated membranes in the next stage of development.

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Study of polymer reformed by ion-irradiation

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Reformation of ion irradiated polymer has been studied by positron annihilation measurements and electron resonance (ESR) measurements. Polymer chains are cleaved by ion irradiation, so that some of the scission sites remain as radicals and the others recombine or form crosslinks between polymer chains.

Positronium (Ps), a hydrogen-like bound state of an electron and a positron, is very sensitive to radicals. Ps has two states; para-Ps (p-Ps, spin singlet) annihilates with a mean lifetime of 125ps in a vacuum emitting two γ rays and ortho-Ps (o-Ps, spin triplet) annihilates with a mean lifetime of 142ns emitting three γ rays. When radicals exist, positronium formation is reduced since positrons and excited electrons are captured by radicals. Moreover, positronium quenches by spin conversion with an electron of a radical. By spin conversion, o-Ps becomes p-Ps. This effect is distinctive for o-Ps because of its long lifetime.
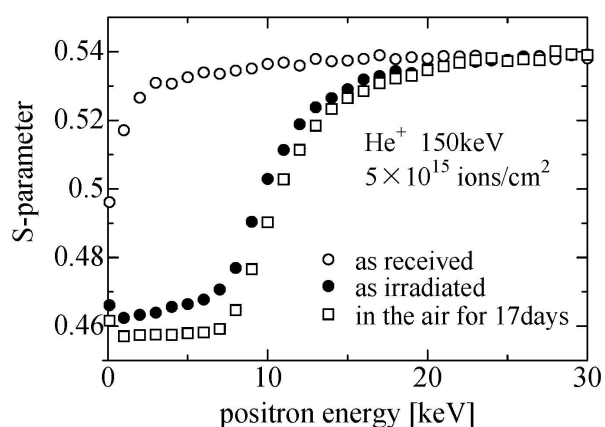
Fig.1 S-parameters of positron annihilation γ ray Doppler broadening peak obtained using a slow positron beam vs. incident positron energy

Figure 1 shows the S-parameters plotted against incident positron energy for the polystyrene irradiated by 150keV He$^+$ ions with fluence of 5×10^{15} ions/cm^2 and that for the as-received sample[1]. S-parameter is the shape parameter of positron annihilation γ ray Doppler broadening peak. The S-parameter for the as-received sample is almost constant, except below 2 keV. The S-parameter for the irradiated samples is lower than that for the as-received sample. The decrease of the S-parameter has been attributed to inhibition of Ps formation by radicals[2]. We found that exposure of the sample to the air makes the S-parameter even lower.

Figure 2 shows ESR spectra for the irradiated polystyrene. The intensity of the singlet peak decreases with time. It should be noted that the time constant for the decrease appears long.
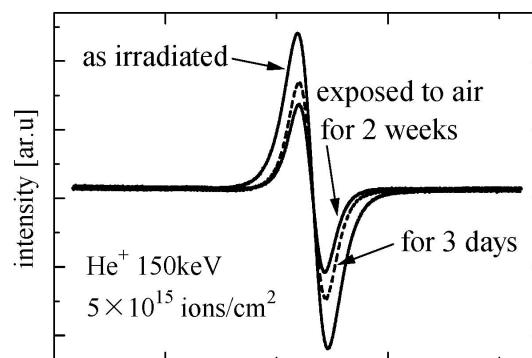
Fig. 2 ESR spectra for irradiated polystyrene exposed to air and as-irradiated

This data indicates that the decrease of the S-parameter by ion irradiation cannot be explained simply by the Ps formation inhibition by radicals[3]. The inhibition may be due to the shielding of coulomb interaction between electron and positron by an abrupt increase of the electric conductivity of ion irradiated polymers[4]. In order to elucidate this problem, the study of ePTFE irradiated by N^{7+} ions using the AVF cyclotron is in progress in RIKEN[5]. Since the ions with energy of 5 MeV/nucleon penetrate deeply into the sample with the thickness of 0.2mm, conventional positron lifetime measurement and positron annihilation γ ray Doppler broadening measurement can be used in addition to slow positron beams measurement.

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Site change of hydrogen in Nb due to interaction with oxygen[†]

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As to an interaction between hydrogen or deuterium and oxygen or nitrogen interstitial solutes in the group Va metals in the periodic table (V, Nb and Ta), H or D is trapped by O or N atoms to form O-H(D) or N-H(D) pairs. From the point of view of hydrogen diffusion, the jump rate of H(D) in those metals, especially in Nb, alloyed with oxygen or nitrogen has been investigated. The existence of O-H(D) or N-H(D) pairs allows measurement of the jump rate at low temperatures otherwise impossible, because hydride precipitation at low temperatures is suppressed due to trapping of H(D). The non-classical behaviour has been observed, and it has been interpreted to be tunnelling motion of trapped H(D) between equivalent two sites around its trapping centre O or N.[1] As the configuration of the O(N)-H(D) pair, various models have been proposed, but it has not been clarified between which sites hydrogen makes tunnelling. In the present study, to obtain direct information on the lattice location of hydrogen in Nb alloyed with oxygen, channelling experiments were performed at room temperature utilizing a nuclear reaction ^{1}H(^{11}B, $\alpha)\alpha\alpha$ with a ^{11}B beam of about 2 MeV.[2,3] Hydrogen can be detected by measuring emitted α-particles.

Specimens are single-crystal of Nb and Nb alloyed with oxygen of 0.3at.% (NbO$_{0.003}$). Hydrogen was doped up to concentrations of 0.0027 and 0.023 in a hydrogen-to-metal-atom ratio for Nb specimens (NbH$_{0.0027}$ and NbH$_{0.023}$), and 0.003 and 0.019 for NbO$_{0.003}$ specimens (NbO$_{0.003}$H$_{0.003}$ and NbO$_{0.003}$H$_{0.019}$). Figure 1 shows the channelling angular profiles obtained for NbO$_{0.003}$H$_{0.003}$ and NbO$_{0.003}$H$_{0.019}$. The channelling angular profiles for both NbH$_{0.0027}$ and NbH$_{0.023}$ are similar to those for NbO$_{0.003}$H$_{0.019}$. It was demonstrated that hydrogen occupies tetrahedral (T) sites in pure Nb.[3] From the comparison of the angular profiles of α-particle yields with those calculated for various kinds of site occupancies, it was demonstrated that H atoms are located at sites displaced by 0.5-0.6 Å from T sites towards their nearest neighbour lattice point in NbO$_{0.003}$H$_{0.003}$, while in NbO$_{0.003}$H$_{0.019}$ most of them are located at T sites and the remains are at the same sites as in NbO$_{0.003}$H$_{0.003}$. The separation between neighbouring equivalent displaced sites is about 0.82 Å. This magnitude is very close to the distance between two sites for hydrogen tunneling, which was estimated from the result of inelastic neutron scattering experiment.[1] The present result supports

the trapping of H by O atoms and the formation of O-H pairs. The number of H atoms trapped by one O atom was estimated to be approximately unity. As the location of trapped hydrogen in the O-H pair, there are possibilities of three types of displaced sites, site-a, site-d and site-j in Fig. 2, with different distances from the O atom but the same separation of about 0.82 Å between neighbouring equivalent sites. It is proposed that the site-a is most probable, which is different from hitherto proposed sites.
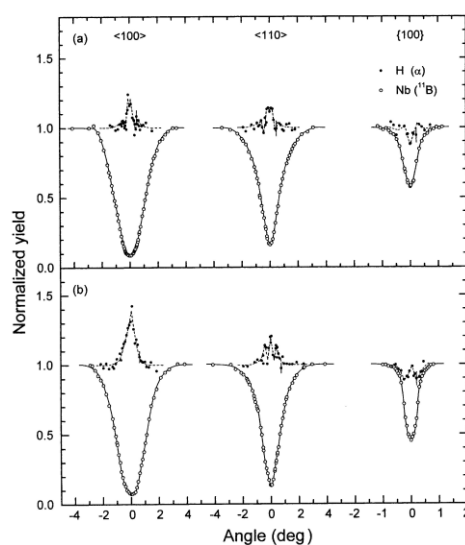
Fig. 1. Channelling angular profiles obtained for (a) NbO$_{0.003}$H$_{0.003}$ and (b) NbO$_{0.003}$H$_{0.019}$ specimens.
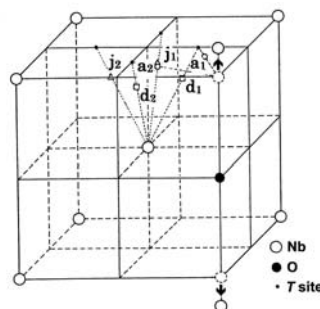
Fig. 2. Three types of probable sites for hydrogen trapped by oxygen.

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Development of a multi-coincidence SIMS analyzer for study on potential sputtering of solid surfaces interacting with highly charged ions

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The interaction between highly charged ions (HCIs) and solid surfaces has been attracting much attention because it induces effectively nanostructure formation[1] and secondary particle emission[2]. The secondary particle emission is also important as an initial process of nanostructure formation. The process is triggered by multi-electron capture by HCIs, and thus the process called "potential sputtering" is essentially different from any kinetic sputtering process. However, the details of potential sputtering by HCIs have not been clarified yet because of the experimental difficulty of separating it from the kinetic processes.

An experimental apparatus for studying the potential sputtering has been developed. The apparatus can simultaneously detect secondary electrons and secondary ions as well as scattered atoms and ions that captured electrons from the surface in off-normal incidence of HCIs[3]. The velocity and charge state of scattered ions can also be analyzed with a Wien filter ($E \times B$ filter) and a parallel plate analyzer, respectively. Therefore, the apparatus allows us to achieve coincidence experiments between time-of-flight secondary ion mass spectrometry (TOF-SIMS) and low-energy ion scattering spectroscopy (LEIS) of the scattered ions with a specific charge state. The coincidence measurement makes it possible to separate the potential sputtering from the kinematic ones. Further, it is also possible to achieve TOF-SIMS analysis of secondary ions in coincidence with that of secondary electrons[4].

Figure 1 shows a schematic illustration of the experimental setup at RIKEN. The charge state of HCI extracted from an electron beam ion source[5] (EBIS) was analyzed by a magnet before this setup. After the adjustment of its trajectory and focus with an electrostatic lens (L) and four deflection plates ($D_{1\perp}$, $D_{1\parallel}$, D_2, and D_3),
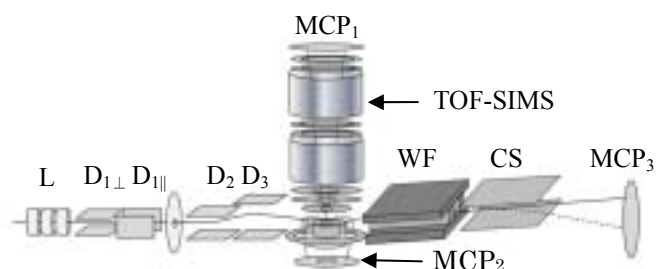
the HCI collides with a target surface at an off-normal or glancing angle. After its velocity and charge state are analyzed with the Wien filter and the parallel plates, ions scattered at the surface were detected by a two dimensional position sensitive detector (2D-PSD) denoted as MCP_3. The time-of-flight of secondary ions (detected on MCP_1) and the three waveforms from the MCP_3 were recorded event by event through a digital oscilloscope. The 2D position on the MCP_3 was obtained from the pulse heights of the waveforms.

The results of coincidence measurements between scattered ions and secondary ions in 2.5q keV Ar^{q+} ($q = 4$ and 6) incident on a GaN(0001) surface have already been reported[3, 4]. It was found that kinetic processes between scattered Ar$^+$ and substrate atoms (Ga or N) on the surface play a role in the proton emission process[6].

The TOF-SIMS analysis can also be achieved by triggering with the signal of secondary electrons detected by MCP_2. An example of the results is shown in Fig. 2 for Ar^{q+} ($q = 4 - 8$) hitting a dodecanethiol($C_{12}H_{25}SH$)/Au(111) sample at 12° (tangential to the surface). The molecular ions fragmented from the alkane chain $(CH_2)_{11}$ and the terminal functional group CH_3 were observed.
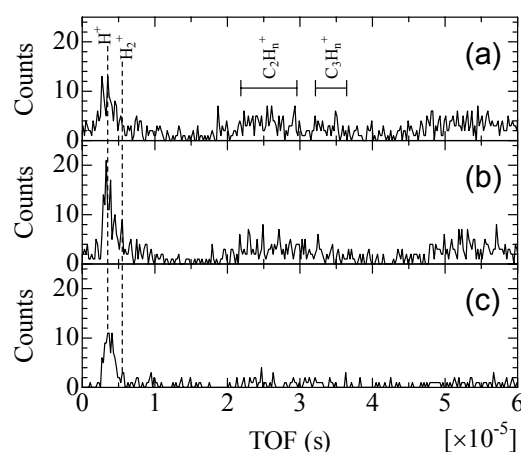
Fig. 2. TOF-SIMS spectra[4] of a dodecanethiol/Au(111) surface interacting with slow (a) Ar^{4+}, (b) Ar^{6+}, and (c) Ar^{8+} at 12° (tangential to the surface).

Fig. 1. Schematic illustration of the experimental setup developed to study the atomic processes of potential sputtering induced by highly charged ions.
L, lenses; D, deflection plates; WF, Wien filter; CS, charge separator; TOF-SIMS, time-of-flight secondary-ion mass spectrometer; MCP, multi-channel plate detectors

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Ion Coulomb crystals in a cryogenic linear RF octupole ion trap

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Ion Coulomb crystals of laser-cooled ions are promising tools for quantum computing[1], studying ultra-cold ion-molecule collisions[2], tests of a possible variation of the fundamental physical constants[3] and precision laser spectroscopy of unstable nuclear ions[4]. A systematic study of ion Coulomb crystals was performed in Penning and Paul ion traps including its linear configurations so far. Laser cooling experiments in linear RF multipole ion traps and in particular an octupole trap have so far not been performed before our experiment[5]. New features of Coulomb crystals not present in a linear Paul trap are expected in a higher order multipole trap due to the large almost field-free region in the middle of this trap.

Here we report the first observation of ion Coulomb crystals in a cryogenic linear RF octupole ion trap. Large and small Coulomb crystals of laser-cooled Ca^+ ions have been observed. In addition we have systematically investigated the changes of the shapes of the crystals by varying the axial static voltages (V_{z0}) and the asymmetric DC voltages (V_{dc}).

The experimental setup is as follows. The octupole trap consists of eight cylindrical electrodes with a diameter of 2 mm. The distance from the center trap-axis to the surface of the electrodes is a larger value ($r_0 = 4.5$ mm) than the normal value ($r_0 = 3$ mm) to increase the field of view. Although this trap configuration is not ideal, larger RF voltages reproduce an almost ideal effective potential. The vacuum chamber enclosing the ion trap is evacuated by a turbo molecular pump and an ion pump. In addition, the ion trap is mounted on a liquid-nitrogen vessel to obtain an ultra-high vacuum with $P < 10^{-8}$ Pa. For laser cooling of Ca^+ ions, two grating stabilized laser diodes ($\lambda = 397$ nm and 866 nm) are used. Both the laser frequencies are locked to the temperature-controlled optical cavities. The laser-induced fluorescence (LIF) at 397 nm is observed by a cooled CCD camera at a right angle to the trap axis. The magnification of the lens system is $6\times$. A UV filter is used for the reduction of background photons.

Examples of the CCD images are shown in Fig. 1. For relatively small axial voltages, long prolate shapes of the ion crystals are observed when applying V_{dc}, while spherically symmetry shapes are observed for larger axial voltages (Fig. 1(a)). The clear shell structure can be recognized inside the crystals composed of ~400 ions. The estimated interval between the shell is 40-50 μm. Because of the small micromotion am-

plitudes in the central trap region, the clear shells are constructed. Single-ion sensitivity was also obtained as shown in Fig. 1 (b). The ions are not arranged like a string, but distributed in the oval with the ion-ion distance of about 70 μm.

When a much larger number of ions are crystallized, the strange shape of the crystal emerges as shown in Fig.1 (c). The image was observed by setting the laser frequency to the position indicated by the arrow in the laser cooling spectrum of Fig. 1 (d). The number of ions is estimated to be $N > 10^4$ using the uniform number density derived from the Coulomb crystal composed of a small number of ions such as Fig. 1(b). The ion temperature is estimated to be less than 5 mK from the residual Doppler width in the spectrum. Although the image is not clear, we recognize the dip along the trap axial direction. The reason of this interesting property is possibly attributed to the characteristic sum potential in the radial direction[5].

In summary, we have observed ion Coulomb crystals in the linear octupole ion trap for the first time. In the next step, the study of ultra-low energy ion-molecule collisions using a Stark decelerator is planned.
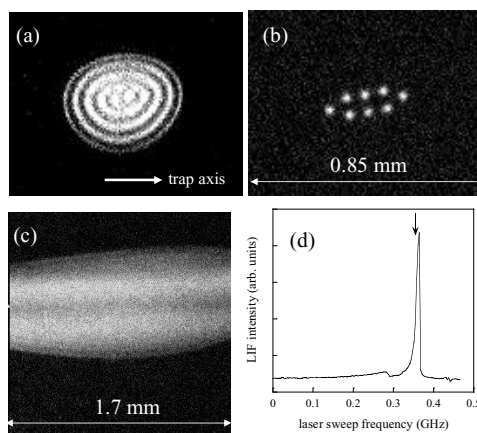
Fig. 1. Observed CCD images of the Coulomb crystal. The trapping parameters are $f_{rf} = 6.04$ MHz, $V_{ac} = 157$ V, and (a) $V_{z0} = 3.40$ V, $V_{dc} = 0.60$ V, (b) $V_{z0} = 0.20$ V, $V_{dc} = 0$ V, (c) $V_{z0} = 0.80$ V, $V_{dc} = 0$ V . The scale in the images of (a) and (b) is same.

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Excitation spectrum of In atoms in superfluid helium

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H. Odashima,[*2] and Y. Matsuo

Laser spectroscopy in superfluid He (He II) is useful for determining the spins and moments of unstable nuclei. We are planning to perform a systematic study of nuclear spins and moments of unstable nuclei stopped in He II, using laser-radiowave(RF)/microwave(MW) double resonance.[1] Atomic polarization by optical pumping, however, has been achieved only with alkali and alkali-like elements, whose electronic energy level structure is rather simple.

On the other hand, non-alkali elements require a number of lasers of different wavelengths to achieve optical pumping due to their complicated energy level structures. To overcome this problem, we will use the unique spectral feature of atoms in He II. In general, the excitation spectra of atoms in He II are blue-shifted and significantly broadened from those in a vacuum due to interaction with surrounding He atoms.[2] By using this characteristic, we expect that atomic polarization of non-alkali atoms by optical pumping can be achieved using a single laser.

Among non-alkali atoms, the Indium atom is an interesting candidate for generating atomic polarization. Indium has a proton number close to the magic number, while the electronic level structure of the third group elements such as In is not too complicated. To obtain a high atomic polarization, the wavelength of the excitation laser should be tuned to the absorption peak. However, a previously reported peak wavelength had large experimental uncertainties because the laser power correction was not sufficient. In this study, we measure the excitation spectrum of In in He II to obtain the absorption wavelength at the peak of the blue-shifted spectrum.

Figure 1 shows the experimental setup for spectrum measurement of In atoms in He II. The apparatus consists of a cryostat with quartz windows, a detection system, and three lasers. The bottom part of the cryostat contains liquid He. An open-top quartz cell is placed above the liquid surface and is filled with He II by utilizing the fountain effect of He II. An In sample is irradiated by an ablation laser to introduce In atoms, ions, and clusters into He II. Because clusters are predominantly produced in laser ablation compared with atoms, the clusters are dissociated using a dissociation laser, typically producing 10^6 atoms in the observation region. The atoms that absorb the excitation laser light are excited from the ground $P_{1/2}$ state to the $S_{1/2}$ excited state, and emit fluorescence. The fluorescence is discriminated with a monochromator fixed at an In emission wavelength of 451 nm, and detected by a photomultiplier tube (PMT). The detection signal is captured by a gated integrator and recorded in a computer. In this experiment, pulsed dye lasers with four types of dyes are used to cover the excitation wavelengths from 350 nm to 390 nm. The spectrum observed using each dye is normalized for laser intensity. The normalized spectra are then combined with each other.
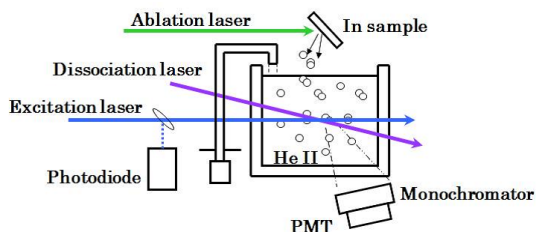
The obtained excitation spectrum of In atoms is shown in Fig. 2. The wavelength of the excitation peak observed at approximately 370 nm is found to be 5 nm longer than that previously reported.[3] Atomic polarization will hence be produced efficiently by optical pumping in the vicinity of 370 nm. To determine the absorption peak position more precisely, we are planning to measure the excitation spectrum around the 370 nm wavelength in detail. An optical pumping experiment of In atoms using a 370 nm laser is also in progress.
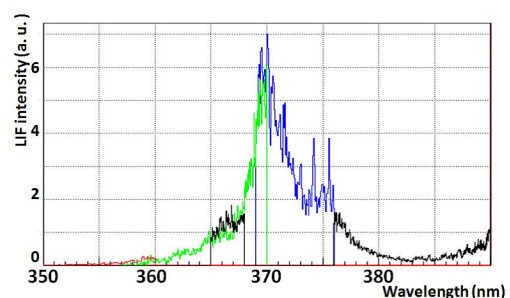
Fig. 2. Excitation spectrum of ^{115}In in He II. The excitation peak is observed at approximately 370 nm. LIF intensity fluctuates due to fluctuation in the number of atoms in the ablation and dissociation processes.

Fig. 1. Experimental setup.

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2. Atomic and Solid State Physics(muon)

Installation of a new laser system for laser-irradiated pump-probe type μSR experiments at RIKEN-RAL muon facility

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Q-switched lasers (1-200 ns pulse duration) are ideally matched to pulsed muon sources (100 ns pulse duration) and yet so far there were only very few experiments that used lasers for synchronized sample excitations[1,2]. Use of laser pulses synchronized with muon implantation provides an extremely useful tool that extends the scope of μSR spectroscopy. Depending on the photon energy, the laser irradiation will cause coherent electron excitation or ionization in the studied sample or even affect the muonium state directly (e.g. convert diamagnetic Mu$^-$ state to paramagnetic Mu). Additionally, circularly polarized light can induce spin polarization of the excited electrons in the sample. The effects of the pump laser pulse on the sample can then be sensitively probed using μSR technique. The time difference between the muon implantation and the laser irradiation can be easily controlled on a nanosecond scale and such pump-probe experiments can then also provide measurement of the decay time constant of the generated excitation.

To allow routine use of such pump-probe technique we have built a dedicated laser room and laser beam delivery system next to the ARGUS μSR spectrometer (Fig. 1) at RIKEN RAL muon facility. The laser system was build by pooling equipment together in close collaboration between RIKEN, KEK, Yamanashi University, University of California and ISIS and is based on an optical parametric oscillator (Continuum Panther EX OPO) pumped by a Nd:YAG laser (Continuum Powerlite 9025). The OPO parameters are summarized in Table 1.

The laser, operating at 25 Hz, is fired at every second muon pulse (50 Hz) so that half of the data is taken with *laser-on* and half with *laser-off*. The output is linearly polarized and we have additionally built an optical setup for sample irradiation with left-hand and right-hand circularly polarized light including pulse-to-pulse control of the polarization.

The laser parameters, such as the wavelength, pulse energy and timing, are controlled in a user friendly manner consistent with the computer control of other
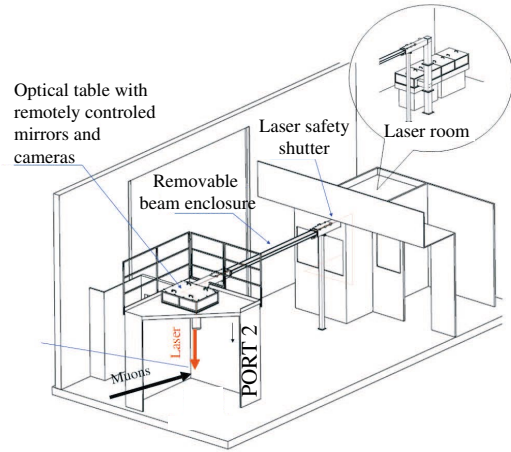
Fig. 1. Layout of the laser enclosure and beam delivery to μSR sample

Wavelength range (signal)	400 - 700 nm (3.1 - 1.8 eV)
Wavelength range (idler)	715 - 2500 nm (1.7 - 0.5 eV)
Pulse energy	1-70 mJ
Pulse duration	9 ns
Repetition rate	25 Hz
Polarization	Controlled pulse-to-pulse (linear, circular, elliptical)

Table 1. Summary of the OPO laser parameters

experimental parameters such as magnetic field or sample temperature.

The laser beam is steered onto the sample through a light-tight beam delivery system using broadband HR mirrors (R>99% over 350-1150 nm), some of which are remotely controlled. Samples are typically mounted in a vacuum chamber on mini-cryostat capable of reaching temperatures of about 15 K. Different mirror and sample configurations are possible where either the front or rear surface of the sample is irradiated.

The system can be also used for experiments at discrete Nd:YAG wavelengths (1064 nm, 532 nm, 355 nm) - see e.g. recent experiment on reaction dynamics of muonium[3].

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Muons for Spintronics: Spin Exchange Scattering of Muonium with Laser-Induced Polarized Conduction Electrons in *n*-Type GaAs

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In order to develop materials and spin injection methods for spintronics, it is essential to establish the experimental methods by which to detect conduction electron polarization (CEP).

In the case of GaAs, because of a large spin-orbit interaction and a direct band gap, CEP can be produced through the electron excitation from a valence-band by circularly polarized (CP) laser and CEP detection is also performed with optical methods [1]. In contrast, for Si, Ge or Graphite, the optical methods can not be applied due to a small spin-orbit interaction and an indirect band gap.

Use of polarized ortho muonium (Mu, a bound state of positive muon (μ^+) and electron with spins aligned in the same direction) is a sensitive tool for CEP detection; the spin of the electron bound to μ^+ can be affected by a replacing it with a polarized conduction electron through an exchange scattering between the Mu electron and the electron in a conduction band. This muon method was proposed at KEK by Torikai et al. [2]. The present experiment is a feasibility study of the muon method to detect CEP in n-type GaAs whose properties are well known [1].

The experiment was conducted at Port 2 of the RIKEN-RAL Muon facility using a pulsed 4 MeV positive muon beam.   The sample used was 360 μm thick 50.8 mm diameter single crystalline GaAs with 3×10^{16} cm^{-3} Si doping. The tunable laser light around 831 nm with a repetition frequency of 25 Hz was generated using a widely tunable OPO system pumped by 355 nm Nd:YAG laser. The linearly polarized laser was passed through an optical setup that converts the linearly polarized light to circularly polarized light illuminating the sample. Here, Pockel's cell (PC) is used for pulse-to-pulse control of switching between right-hand CP light ("R") and left-hand CP light ("L"). A laser pulse with a pulse length of 10 ns was arranged to irradiate the GaAs sample at 1 μs after muon pulse.

The sample was placed in a strain-free manner by using a specially designed sample holder containing He gas.

The typical μSR time spectrum under 0.1 T at 15 K with laser irradiation is shown in Fig. 1, representing data under the conditions of "L" and "R" with reference to "Off". An exponential relaxation component corresponding to BC-Mu (Mu at body-center site) state observed in the "Off" data exists after laser irradiation, almost as it did in terms of amplitude and relaxation rate before irradiation. An insensitive response of BC-Mu to laser irradiation can be concluded.

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The "L-R" effect has a characteristic dependence on the external field. The effect which clearly exists below 0.1 T disappears above 0.2 T. There, the hyperfine magnetic field from the bound electron is decoupled by the external field so that the polarization change of the bound electron does not affect μ^+ polarization. Since the BC-Mu is now known to be insensitive, the muon state responding to the laser should be concluded as   T-site Mu (Mu at tetrahedral site) state and/or Mu$^-$ (bound state of μ^+e$^-$e$^-$) state.

We then measured the dependence of the polarization effect on laser power by reducing laser power from 2.25 mJ down to 0.4 mJ. An increase of the "L–R" polarization effect with reference to "Off–On" effect was observed, which is consistent with the result of the increased spin life time against decrease of laser power in this power range observed in the optical measurement [1].

Also, by raising temperature, although the "On-Off" effect stays unchanged, the "L–R" effect began to disappear. The result is again consistent with decreased spin life time at higher temperature observed by the optical method [1].

In conclusion, the exchange scattering of the muonium was proved to detect CEP produced by circularly polarized lasers in *n*-type GaAs. Correct response of the signal was obtained, which is consistent with the CEP properties of the n-type GaAs sample known through the optical measurement [1]. The result of the present feasibility measurement for *n*-GaAs is encouraging for the muon method to be applied to CEP detection in many other spintonics materials such as Si, Ge, Graphite, etc.

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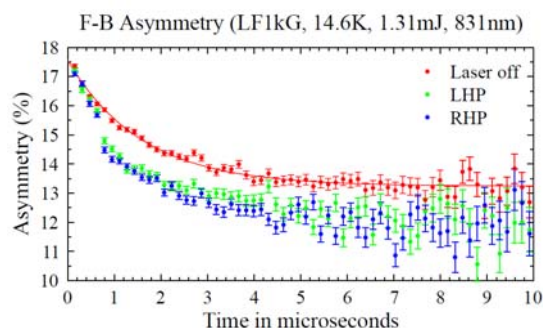
Fig. 1. The μSR time spectrum at 15 K and under 0.1 T with 3 laser conditions at 1 μs after muon pulse;   "Off" is shown by red points, "L" (Para) is shown by green points and "R" (Anti) is shown by blue points. A clear polarization effect can be seen.

Discovery of Spin-Dependent Response of Negative Muonium (Mu⁻) to Laser Induced Polarized Electrons in *n*-Type GaAs under Zero Field

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Y. Matsuda[*], K. Ishida, K. Ohishi, F.L. Pratt[3], I. Shiraki[4] and E. Torikai[4]

In order to promote the spintronics, a use of spin-dependent exchange scattering between a polarized electron in ortho muonium (ortho-Mu, μ^+e^-, a bound state of positive muon and an electron with the spins aligned in the same direction) to detect the conduction electron polarization (CEP) in semiconductors has been proposed at KEK by Torikai et al. [1]. Recently a feasibility study of the method was successfully carried out on a strain-free *n*-type GaAs (3×10^{16} cm^{-3} Si) by measuring a change in the μ^+ polarization in Mu against a relative directional change of the polarization under external longitudinal fields above 20 mT [2]. In *n*-type GaAs, CEP is produced by circularly polarized (CP) lasers due to a strong spin-orbit coupling and a direct band-gap. Observations consistent with the properties of the CEP known in optical experiments were obtained in the feasibility study [2].

On the other hand, the properties of muonium in undoped and doped GaAs have been thoroULy studied. The existence and properties of Mu⁻ ($\mu^+e^-e^-$, a diamagnetic bound state of μ^+ and the two electrons with a singlet coupling at the ground state) in n-type GaAs with Si doping concentration higher than 10^{16} are known [3].

During the course of the feasibility experiment [2] conducted at Port 2 of the RIKEN-RAL, the present measurement was conducted by using a pulsed 4 MeV positive muon beam. A surprising spin-dependent response of the Mu⁻was found.

The tunable laser light around 831 nm/1.49 eV with 25 Hz repetition frequency was generated using a widely tunable OPO system. As described [2], linearly polarized laser output was converted to CP light illuminating the sample. The Pockel's cell (PC) is used for pulse-to-pulse switching between right-hand CP light ("R") and left-hand CP light ("L"). A laser pulse with a pulse length of 10 ns was irradiated at 1 μs after the muon pulse.

The obtained μSR time spectrum under zero field (ZF) at 15 K (Fig. 1) represents ZF muon spin relaxation data under the conditions of "L" and "R" with reference to "Off".

Combined with other high-statistics measurements, asymmetry amplitudes of the ZF "Off" at 15 K comprises Mu⁻ state with Gaussian relaxation (5.70(6) %) and 1/6 component of both BC-Mu (Mu at body-center site) with exponential relaxation (nearly 1.0 %) and T-Mu (Mu at tetrahedral site) with almost no relaxation (nearly 1.0 %).

In ZF "Off" (Fig. 1), major 5/6 components of full asymmetry of BC-Mu and T-Mu (amounting in total to 14 %) are missing due to hyperfine interaction in Mu and a nuclear hyperfine field on the remaining ortho Mu.

As for the polarization-dependent "L-R" effect, the following observations can be readily obtained: 1) the major component with Gaussian relaxation at "Off", which corresponds to the Mu⁻ state, does change against the change of CP of the laser irradiation; 2) As for the data under longitudinal fields above 20 mT [2], because of an unchanged exponentially decaying component before and after laser irradiation, the insensitive nature of the BC-Mu to the laser irradiation can be concluded. At the same time, the tail region of the relaxation function which represents a 1/6 component of T-Mu does not change. Thus, a major contribution to the ZF "L-R" effect may be concluded to be due to the Mu⁻ state.

In order to confirm the Mu⁻ dominance in "L-R" effect the polarization dependence of the TF rotation under 2 mT was measured with a laser timing set at 100 ns after the muon pulse. The shift of the laser timing was made in order to maximize the polarization effect in TF data. A clear "L-R" effect was observed in the amplitude of the remaining rotating component (0.30(4) %) with a phase shift corresponding to the time delay (0.24(8) μs).

In order to understand the observed Mu⁻ response, a two-step process can be considered; (1) spin-independent one-electron removal collision between Mu⁻ and laser induced conduction electron followed by a formation of ortho Mu (50 %) and (2) spin-dependent ionization in between ortho Mu and polarized laser induced conduction electrons to produce μ^+ in a spin-dependent manner.

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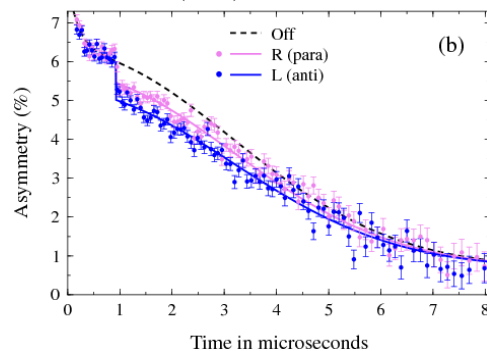
Fig. 1. Muon-spin-relaxation time spectrum under ZF in n-GaAs at 15 K with laser injection at 1 μs, representing the polarization effect.

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Measurement of the Chemical Reaction Rate of Muonium with Stimulated Raman-Pumped $H_2^*(v{=}1)^\dagger$

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Stimulated Raman pumping (SRP) is used to produce H_2 in its first vibrational state, in order to measure, for the first time, the Mu $+H_2^*(v{=}1) \rightarrow$ MuH $+$H reaction rate at room temperature, as a prototypical example of new directions in gas-phase muonium chemistry, utilizing the pulsed muon beam and a new dedicated laser system at the RIKEN/RAL Laboratory.

This experiment will provide new tests of reaction rate theory in the fundamental H_3 system[1,2] in three important ways:

- Since the pumped v=1 state is not in thermal equilibrium, accurate TST calculations are not feasible, mandating rigorous 3D quantum rate calculations.
- The barrier to reaction is so much lower than for the GS, that rigorous calculations of the barrier height, including non-BO corrections, are required.
- At the temperatures of the experiment, quantum tunneling of Mu can be expected to play a major role, in contrast to the GS reaction, providing a further constraint on accuracy of the 3D quantum calculations needed.

The experiment utilizes the 2nd harmonic output of a Nd:YAG laser (532 nm) with pulse energies up to 500 mJ at a repetition rate of 25 Hz exciting up to $8{\times}10^{17}$ H_2 molecules to v=1 state. The muon stopping distribution in pure H_2 at 50 bar has a variance σ of 11 mm and therefore the major difficulty in this experiment, compared to the standard SRP process, is to ensure a homogeneous excitation over a volume of several cm^3 and a sufficient pressure of $H_2^*(v{=}1)$ to ensure a measurable Mu relaxation rate. To optimize all of these requirements different optical setups have been constructed and tested.

Fig. 1. A) experimental signal; B) simulated difference signal (see text)

The first result of this experiment gives a measured relaxation rate due to the laser excitation of $\lambda^* = 0.085 \pm 0.051$ μs^{-1}, consistent with theory but limited by both low statistics and particularly by a high background relaxation rate (about 5 times larger than λ^*). The signal of interest in this experiment is the difference in μSR spectra for *laser ON - laser OFF* defined by $S(t)$ in ref[3]. Most variables in $S(t)$ can be determined from the *laser OFF* experiments (muonium asymmetry A_{Mu}, background relaxation rate λ_0, muonium rotation frequency and phase) and the only parameters that need to be fitited are λ^* and the fraction f of Mu atoms that overlap with the laser pumped $H_2^*(v{=}1)$ volume. Figure 1(A) shows a fit of $S(t)$ to the experimental data for TF of 2.22 G, $\lambda_0 = 0.48$ μs^{-1}, muonium asymmetry $A_{Mu} = (4.32{\pm}0.07)\%$ and f=0.4 giving the above value for λ^*. The poor signal-to-noise ratio observed here should be significantly improved in the future experiments by reducing the background relaxation rate (originating mostly from magnetic field inhomogeneity) which damps the S(t) by a factor of $exp(-\lambda_0 t)$. This is demonstrated in Fig. 1(B) showing simulated data assuming $\lambda_0 = 0.20$ μs^{-1} and improved statistics ($5{\times}10^8$ events). The necessary improvement in the field inhomogeneity can be achieved through either unbalanced control of the existing Helmholz coils or specifically designed compensation coil(s) placed arround the sample cell.

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Progress in design and development of counter system for new μSR spectrometer at RIKEN-RAL

D. Tomono, T. Kawamata, Y. Hirayama[*1], M. Iwasaki[*1], I. Watanabe, K. Ishida and T. Matsuzaki

A new research project to explore various matters under multiple extreme conditions, such as high pressure, low temperature, etc. combined with μSR technique, has recently been launched using the high intensity beam at RIKEN-RAL. For this purpose, a high performance and multi-purpose spectrometer is being developed at the Port-4 area. A multi-segmented detector capable of measuring decay positrons with less signal pile-up, operating photomultiplier tube (PMT) remote from the magnetic field and mounting scintillators in the narrow space is essential for the setup and optimization of the performance of μSR spectrometers. Our recent feasibility test of the prototype counters[1,2] showed that we can selectively observe positrons within 7 degrees from a muon stopping sample using spindle scintillator, wave-length shifting fibers, clear fibers and multi-anode PMT (MAPMT). Based on this test, a new counter system to fabricate the spectrometer has been designed and a data acquisition system was built in parallel.

Figure 1 shows pictures of counters and coils of the new spectrometer. The basic parts shown in Fig. 1 left, are longitudinal Helmholtz coils of 150 mm bore up to field of 0.4 T, transverse coils and 3 pairs of field cancellation coil. The polarization of muons stopped in a sample is determined by two counter assemblies located at the core of longitudinal coils, which were up-and downstream to the muon beam direction. The wavelength shifting fiber of 1.5 mm diameter (Kuraray Y-11(400)MS) is buried at the center of spindle counter ($10 \times 10 \times 40$ or 50 mm^3) [a] and tightly connected the clear fiber of 2.5 m length (Kuraray) as a light guide (Fig. 1 top-right). 16 clear fibers are bundled and connected to the MAPMT (H6568-10-200mod). The 606 counters are mounted in two special bases (Fig. 1 bottom-right). They are attached at the bore of the longitudinal magnet.

Figure 2 shows the muon decay time spectrum using practical 16 counters. Although a constant background component usually exists around 10^{-3} of the statistics at $t = 0$ due to the charged particles outside from the sample, it is not observed, at least, in less than 3×10^{-5} owing to direction sensitive mechanism[1,2].

A scheme of data acquisition system is briefly described in Fig. 3. The VME-based data acquisition with Linux software is built for data acquisition of the counters. The front end software (MACS/Windows[3])

Fig. 1. Pictures of counters and coils. (left) Counter base and coils. At the core of the longitudinal coil, a counter base is installed to mount scintillation counters. The 606 clear fibers mediate photons between counters and PMTs installed beneath coils. (top-right) Counters and optical fibers. (bottom-right) Counters mounted in the counter base.

Fig. 2. Muon decay time spectrum. A constant background component is suppressed in less than less than 3×10^{-5} of the statistics at t=0.

Fig. 3. Schematic figure of DAQ system.

controls overall of the DAQ and slow-control system for temperature and magnet.

In summary, the new μSR spectrometer is designed and being constructed at RIKEN-RAL. The spectrometer installation at Port-4 and commissioning test are currently underway.

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[*1] also Department of Physics, Tokyo Institute of Technology
[a] This scintillator is originally manufactured by TRIUMF group for the T2K near detector. We modified this scitillator for our requirements.

μSR study around a quantum critical point in heavy fermion compounds $\mathrm{Ce_2RhIn_{8-x}Sn_x}$

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Quantum phase transitions have attracted a great deal of attention on both the theoretical and experimental sides. Such transitions occur at zero temperature as a function of an external parameter (i.e., magnetic field, pressure or impurity concentration) which drives the system from an ordered to a disordered state. Heavy fermion compounds provide the opportunity to study such phenomena since the competition between ordering (via the RKKY interactions) and disordering (via the Kondo singlet formation) can easily be experimentally controlled.

The heavy fermion compound $\mathrm{Ce_2RhIn_8}$ is known as an antiferromagnet with $T_\mathrm{N} = 2.8$ K.[1] Recently, it has been found that chemical substitution of Sn for In in $\mathrm{Ce_2RhIn_{8-x}Sn_x}$ depresses T_N with a critical concentration of about $x \sim 0.5$, suggesting the emergence of a quantum critical point.[2] We have performed muon spin relaxation (μSR) measurements on several components of $\mathrm{Ce_2RhIn_{8-x}Sn_x}$ in order to investigate the evolution of magnetic order in this system.

In the previous report,[3] we summarized the zero field (ZF)-μSR results with $x = 0.5$ and 0.7 above $T \geq 0.3$ K. We found that the muon spin relaxation increased below 0.5 K with $x = 0.5$, while the muon spin precession signal was not observed. On the other hand, there was no increase in the relaxation rate with $x = 0.7$ at low temperature. In order to study the observed relaxation below 0.5 K with $x = 0.5$ in detail, we planned to perform ZF-μSR experiments down to 20 mK. However, there was a problem with the dilution refrigerator (DR) so we could not perform μSR experiments with $x = 0.5$ and 0.7 samples down to 20 mK. Hence, we changed the plan. Another important issue is to study the parent material as a reference for microscopically clarifying the systematic change of internal magnetic field with Sn-substitution. We have performed μSR experiments on $\mathrm{Ce_2RhIn_8}$ at temperatures from 0.3 K to 5.0 K on a single crystal flat plate with the c axis along the muon beam. The μSR measurements were conducted at the RIKEN-RAL Muon Facility in the Rutherford Appleton Laboratory, UK. In this report, we present preliminary results.

Figure 1 shows the ZF-μSR time spectra at 3.7 K and 0.3 K. At higher temperatures above T_N, the time spectra consist of two components, i.e., one showing slow relaxation $P_z(t)$ due to random local fields from nuclear magnetic moments, and the other mostly independent of time. More specifically, we have $A(t) =$
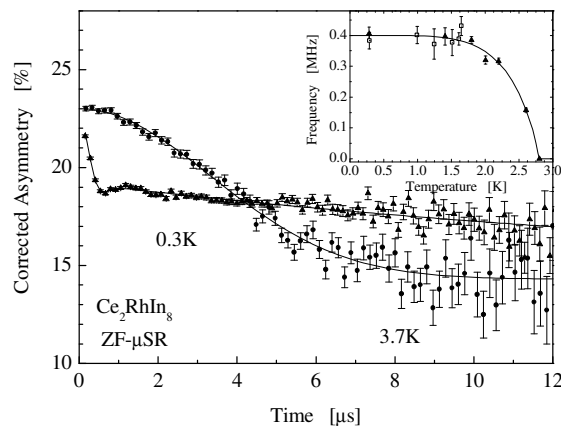
Fig. 1. ZF-μSR time spectra in $\mathrm{Ce_2RhIn_8}$ at 3.7 K and 0.3 K. The solid lines are fits as described in the text. Inset shows the temperature dependence of muon spin precession frequency below T_N. The line is guide for the eyes.

$AP_z(t) + B$, where A and B are the initial μ-e decay asymmetry for the respective component, and $P_z(t) = \exp(-\Delta^2 t^2)$ with Δ/γ_μ being the rms value of random local field (where $\gamma_\mu = 2\pi \times 135.54$ MHz/T is the muon gyromagnetic ratio). The time spectra were well reproduced by the above formula with $\Delta \simeq 0.214(5)$ μs^{-1} which is mostly due to ^{113,115}In nuclear moments and is consistent with the previous results.[3] The second "background" component is attributed to the silver sample holder and A/B is estimated to be 0.589(14). For $T < T_\mathrm{N}$, we found that $P_z(t) = (1-s)\exp(-\sigma^2 t^2)\cos(2\pi f t + \phi) + s\exp(-\lambda t)$ reproduces the spectra, where σ and λ are the relaxation rates, f is the muon spin precession frequency under a local field H_loc, ϕ is the initial phase and s is the fraction. As shown in Fig. 1, a clear precession signal was observed below T_N. The volume fraction of the antiferromagnetic component at 0.3 K was estimated to be $\sim 56\%$. The temperature dependence of f is shown in the inset of Fig. 1. The f increases below T_N with the development of the internal magnetic field, while the temperature dependence of s does not show any change.

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On the exotic magnetic ground state in bond-disordered quantum spin system IPA-Cu(Cl,Br)$_3$

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The quantum spin system (CH$_3$)$_2$CHNH$_3$-Cu(Cl$_x$Br$_{1-x}$)$_3$ abbreviated as IPA-Cu(Cl$_x$Br$_{1-x}$)$_3$ is a solid solution of two spin gap systems (CH$_3$)$_2$CHNH$_3$-CuCl$_3$ and (CH$_3$)$_2$CHNH$_3$-CuBr$_3$, whose energy gaps are 14 K and 98 K respectively. So far, macroscopic experiments on this system have indicated that it becomes gapless and show a magnetic order at T_N=12-18K depending on x only when x is within the limited region between the two quantum critical points (QCPs) of $x_C = 0.44$ and 0.87, and otherwise it possesses a spin gap [1]. However, theoretical investigation by the quantum Monte Carlo method showed that the region of $x<0.44$ should be gapless though the occurrence of magnetic order is critical [2].

We have investigated by muon spin relaxation (μSR) the ground state of the two samples with x=0.40 and 0.45, which straddle the QCP x_C=0.44. Experiments were performed at both RAL and PSI. The incident muon beam was directed parallel with the b^*-axis of aggregation of crystals which were aligned and set onto the silver plate[2].The muon spin relaxation in both the samples over the entire temperature and field region was described by a function containing two components expressed as

$A_1 G_{KT}(\tau, \Delta)\exp(-t/\lambda_1) + A_2\exp(-\tau/\lambda_2)$

where G_{KT} is the Kubo-Toyabe function with parameters of a static field distribution width at the muon site Δ, relaxation rates λ_1 and λ_2, and component amplitudes A_1 and A_2. The static field distribution width Δ was around 0.2 (μs^{-1}), temperature independent within the experimental resolution, and considered to be due to the nuclear contribution. The magnitude of λ_2 always exceeded λ_1 by more than ten times. These results mean that the sample is intrinsically in a microscopic phase separation of the two phases, namely, the magnetic region with microscopic island form corresponding to λ_2, and the singlet-like sea, which corresponds to λ_1 and surrounds the former[3]. The amplitude fraction of λ_2 was $A_2 \approx 10$ % in the sample x=0.40 at 8 K, increased with decreasing temperature, and reached 0.4 below 4K and stayed constant down to 15 mK. With x=0.45, A_2 reached 0.36 at 2 K.

No muon spin rotation due to a static field by a magnetically ordered phase was observed in either sample. This fact supports the macroscopic experiments in the x=0.40 case [1]. However, the relaxation rate of the fast component λ_2 significantly increases with decreasing temperature and reaches an anomalously large value below 1 K. This means that a dynamical spin fluctuation with a large amplitude remains down to 15 mK. The frequency spectrum of this spin fluctuation was previously investigated at RAL in a limited temperature region down to

0.3 K, where we found that the spin fluctuation slows down with decreasing temperature [3]. This behavior was interpreted as the soft-mode toward a possible magnetic phase transition at absolute zero such as Bose-glass phase.

The exotic phase was first predicted theoretically by Fisher et al.[5] as a ground state of disordered Boson systems in which particles are in a gapless state and still are localized. The soft mode that corresponds to the Bose glass is expected to be distributed over a finite region in q-space, rather than to be restricted in a well-defined q-point as in conventional structural phase transitions. The fact that the muon is a local probe allows one to detect such an unconventional soft mode. The present experiment provides a further evidence of the possibility that the ground state of the system with $x \leq 0.45$ is the Bose-glass, which is magnetic and still does not order at finite temperature.

Next, our observation of no magnetic order with $x = 0.45$ down to 2 K, as shown in Fig. 1, indicates that the previously reported value of the quantum critical point $x_C = 0.44$ [1] should be modified to be at least larger than 0.45.
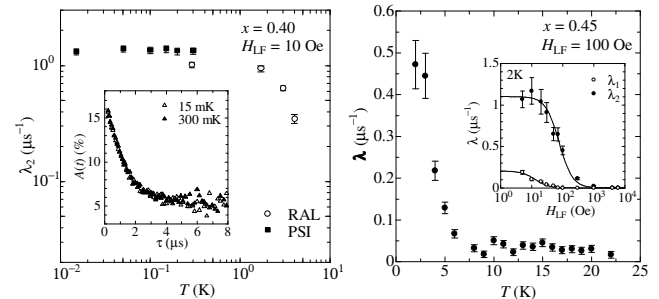
Fig. 1 Temperature dependence of the muon spin relaxation rate λ_2 with x=0.40 (left) and 0.45 (right). Insets of the each figure shows typical relaxation curves and LF decoupling respectively.

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Microscopic investigation of the crossover from impurity-induced order to pressure-induced order in $Tl(Cu_{1-x}Mg_x)Cl_3$ by muon-spin-rotation/relaxation

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[spin gap, impurity, crossover, magnetic order, pressure]

In $TlCuCl_3$ system, field-induced magnetic ordering has been investigated extensively, and the obtained results are qualitatively well described by the magnon Bose-Einstein condensation theory[1]. Pressure-induced magnetic ordering has also been reported in $TlCuCl_3$. It is reported that the critical pressure P_c is 0.42 kbar, and that the pressure-induced ordered state is an antiferromagnetically ordered state of which the magnetic structure is the same with the case of the field-induced phase. In the impurity-introduced $Tl(Cu_{1-x}Mg_x)Cl_3$ system, the magnetic phase transition to an ordered state is observed by magnetization and specific heat measurements. Recently, Imamura et al. reported the pressure-induced magnetically ordered phase by magnetization measurements in $Tl(Cu_{1-x}Mg_x)Cl_3$, and concluded that the change from the impurity-induced phase to the pressure-induced phase is the crossover[2]. In orer to clarify the microscopic difference between magnetic states induced by pressure and by impurity doping, we carried out muon-spin-rotation/relaxation (μSR) measurements at the RIKEN-RAL Muon Facility using the newly installed gas-pressurized μSR setup[3].

The magnetic phase transition at ambient pressure is determined by the magnetization measurement to be $T_N = 2.85$ K for $x = 0.015$. Figure 1 (a) shows Zero-field μSR (ZF-μSR) time spectrum under various pressures at 2.3 K. Each plot is shifted consecutively for clarity. All spectra are analyzed using the two component function of $A(t) = A_1 e^{-\lambda_1 t}\cos(\omega t + \theta) + A_2 e^{-\lambda_2 t}G_z(\Delta, t)$. The first term is the signal from samples, and the second term is that from the large pressure cell. λ_1 and λ_2 are the muon-spin-relaxation rate, and ω is the muon-spin-rotation frequency. $G_z(\Delta, t)$ is the static Kubo-Toyabe function. The ratio of the amplitude of signal from samples and the pressure cell A_1/A_2 is 0.16. Fitted results are shown in Fig.1 as solid lines. Above 0.5 kbar, the muon-spin-rotation is observed although no rotational signal is observed in ambient pressure. The rotational signal indicates that a long-range coherent ordering appears above 0.5 kbar. The internal magnetic field H_{int} at the muon sites are deduced using the relation of $H_{int} = \omega/\gamma_\mu$ (open circles in Fig. 2). To determine whether or not the fast relaxation originates from a static internal magnetic field,
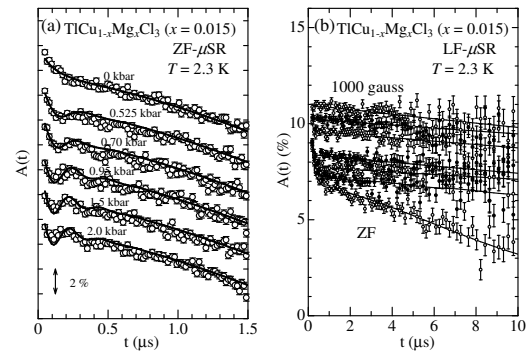
Fig. 1. (a) Time spectra of the ZF-μSR at 2.3 K under pressures. (b) Time spectra of the LF-μSR at 2.3 K in ambient pressure.
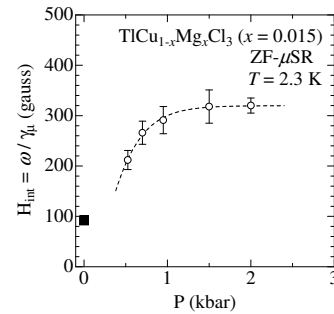
Fig. 2. Pressure dependence of the internal magnetic field at muon sites. Dashed line is guide for the eye.

the longitudinal-field muon-spin-relaxation (LF-μSR) measurements are carried out in ambient pressure using a usual cryostat. Time spectra of LF-μSR at 2.3 K are shown in Fig.1 (b). The typical behavior in the presence of a static internal magnetic field at the muon sites is observed. By analysing this decoupling pattern under the assumption that H_{int} has a unique magnitude but random directions to LF, H_{int} at the muon sites is estimated to be 92 gauss at 2.3 K (a closed square in Fig.2). Deduced H_{int} from the rotation frequency and LF data are summarized in Fig. 2. From these results, we conclude that the crossover reported by Imamura et al.[2] is the continuous change from a short-range order to a long-range coherent order without the quantum critical point.

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Quantum critical behavior in highly random systems $Tl_{1-x}K_xCuCl_3$ probed by zero- and longitudinal-field muon spin relaxation

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[spin gap, magnon, soft mode, randomness]

In the mixed system $Tl_{1-x}K_xCuCl_3$, the spatial randomness of the local chemical potential is introduced through the difference of the value of the dominant intradimer interaction J between $TlCuCl_3$ and $KCuCl_3$, because J corresponds to the local potential of magnons. Magnetization measurements suggest that the ground state is a magnetic state with finite susceptibility in the mixed system in zero field (ZF), although finite excitation gap remains[1].

Recently, we have reported results of μSR measurements on $Tl_{1-x}K_xCuCl_3$. As for $x = 0.20$, the increase and the saturation of the muon spin relaxation rate λ were observed at low temperatures, which is possibly a precursor to the Bose-glass phase[2]. In the case of $x = 0.44$ and 0.58, the increase of λ is observed, which suggests the slowing down of the frequency of the Cu-$3d$ spin fluctuations toward a spin frozen state below 20 mK in contrast to the predicted Bose-glass phase, and the root-exponential-like behavior of the time spectrum indicates that the origin of the relaxation is possibly the spatially-fixed fluctuating dilute moments[3,4]. However, the spin dynamics, which is the frequency spectrum of spin fluctuations, has not yet been clarified under the conditions that the randomness is enhanced with increasing the concentration of x and that the divergent increase of λ is observed. In order to investigate microscopic dynamical magnetic properties in highly random systems, we carried out the zero- and detailed longitudinal-field muon spin relaxation (ZF- and LF-μSR) measurements in $Tl_{1-x}K_xCuCl_3$ with $x = 0.51$ and 0.60 single crystals at the RIKEN-RAL muon facility.

Figure 1(a) shows the LF-μSR time spectrum at each temperature in the longitudinal field of 3950 gauss. With decreasing temperature, the time spectrum becomes to show a faster relaxation down to 3 K, however, below 3 K, the spectrum shape goes back to those of higher temperature, i.e., the relaxation becomes slower. To discuss the temperature change of the spectrum and the muon spin relaxation rate λ, the LF-μSR time spectra are analyzed using the stretched exponential function $A(t) = A_0 \exp(-\lambda t)^\beta$. Figure 1(b) shows the deduced relative temperature change of the muon spin relaxation rate λ in each longitudinal field. In 3950 gauss, peak structure in the relative
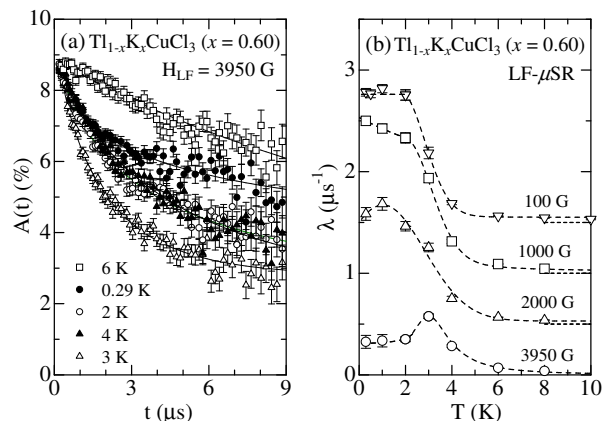
Fig. 1. (a) Time spectra of the LF-μSR in 3950 gauss. Solid lines are fitted results. (b) Relative temperature change of the muon spin relaxation rate λ in each longitudinal field. Dashed lines are guide for the eye. Each plot is shifted upward consecutively by 0.5 μs^{-1} for clarity.

temperature change of λ is observed at $T \sim 3$ K. We have to notice here that a unit of λ is practically an arbitrary unit, because power β shows the large temperature dependence and the change of β affects the absolute value of λ. Thus, we can only discuss the relative change of λ in this case.

The temperature where the peak is observed decreases with decreasing the magnetic field. The muon spin relaxation rate λ in the LF corresponds to the wave-vector(q) -integration of the generalized dynamical susceptibility. In other word, the H_{LF} dependence of λ corresponds to the frequency ($\omega_{LF} = \gamma_\mu H_{LF}$) spectrum of spin fluctuations, where γ_μ is the gyromagnetic ratio of the muon spin. Therefore, observed peak shift to lower temperatures with decreasing H_{LF} is the observation of the slowing down of Cu-$3d$ spins fluctuation frequency, and is interpreted as the soft mode of spin waves toward a possible magnetic phase transition. In the case of $x = 0.60$, the change of λ saturates in low magnetic fields. This result indicates that ground state at the zero temperature is not magnetic, and the system is in the vicinity of the quantum critical point.

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Changes of spin dynamics in multiferroic $Tb_{1-x}Ca_xMnO_3$

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[Multiferroic, Relaxor, Ca-doped manganite]

Recently, an interesting effect was found in the Ca-doped $TbMnO_3$ single crystal showing typical response of relaxor ferroelectric at 5% Ca doping level as revealed by the temperature dependent dielectric response as well as the neutron diffraction measurement on a single-crystalline sample[1]. This relaxor behavior was suggested to be related to the ferroelectric properties of this material well known to have a magnetic origin. The effect was further suggested to be associated with the weakening of the next-nearest neighbor superexchange interactions[2]. However, this suggested weakening decoupling has yet to be observed directly. The effect of Ca doping on the magnetic ordered state

Fig. 2. ZF-μSR spectra of $Tb_{1-x}Ca_xMnO_3$ with x=0, 0.05 and 0.1 at 10 K.
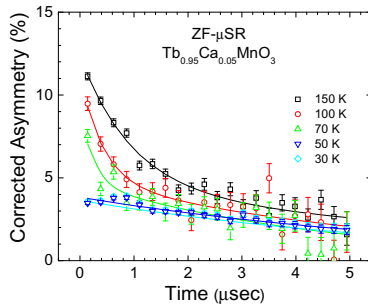
Fig. 1. Temperature dependence of the corrected asymmetric of zero-field fast muon relaxation in $TbCa_{0.05}MnO_3$.
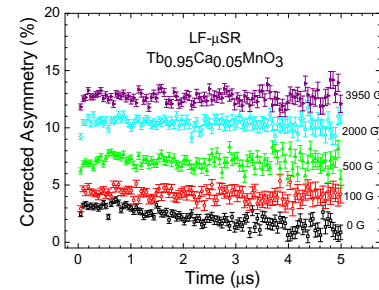
Fig. 3. LF-μSR spectra at 10 K for 5% Ca doped $TbMnO_3$

was investigated here by a ZF-μSR measurement carried out at various temperatures on the 5% Ca-doped single crystal at the RIKEN-RAL Facility in UK. The time spectra in Fig.1 show a fast depolarization behavior around 100 K. With decreasing temperature and hence increasing effective internal field, the initial depolarization process took place at a faster pace and became a sharp drop below about 50 K. This means that the spin fluctuations of Tb and/or Mn moments in this sample were weakened with decreasing temperature at a much faster rate as compared to the undoped case where the depolarization process remains observable at 40 K. This effect was further investigated by the measurement carried out at 10 K. Figure 2 shows the comparison between the effects of different Ca doping concentrations at that temperature. The same behavior is exhibited by the 5% Ca-doped sample at this temperature in contrast to the flat behaviors shown by the undoped and the 10% Ca-doped samples supposedly associated with homogeneous internal field.

Finally, the measurement was repeated at the same

temperature in various applied longitudinal fields (LF). The result presented in Fig.3 clearly shows a magnetic ordered state at 10 K. Admittedly the correct decoupling field is difficult to estimate from the data because some non-intrinsic instrumental effects induced by LF resulted in unexpected shift in the baseline of the spectrum. However, a comparison of these time spectra with those obtained at 10K and zero LF, shows that the asymmetry lost in ZF was gradually recovered with increasing LF. However the less than complete recovery seems to indicate that the internal field is too large for the muon to be decoupled from it even at 4 kG.

We note that no sign of coherent muon-spin precession was observed due to the limited time resolution of the pulsed muon beam, and additional investigations is needed using the dc muon beam with higher time resolution. Nevertheless, our current data do suggest the possible appearance of inhomogeneous internal field due to the 5% Ca-doped $TbMnO_3$, which is not inconsistent with the inhomogeneous nature of the spin alignment revealed by the neutron scattering measurement[1].

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μSR study of the spin-lattice cooperative phenomenon of RbCoBr$_3$

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[μSR, frustration]

In the frustration system, cooperative phenomena between different degrees of freedom have recenrty attracted interest. RbCoBr$_3$ is on the ABX$_3$-type compounds which are well-known frustrated magnets. ABX$_3$-type compounds have –BX$_3$– linear chains of infinitely connected face-shared BX$_6$ octahedral run along the c-axis. The chains form an equilateral triangular lattice in the c-plane, forming a triangle pillar.

RbCoBr$_3$, which shows both magnetic and structural phase transitions, is a new compound in the ABX$_3$-type system. Neutron scattering measurement showed a linear increase in the intensity of the (111) magnetic Bragg peak with decreasing temperature below the ferrimagnetic transition temperature, $T_{N2} \sim$ 31 K.[1] This unusual result is successfully reproduced by a new spin-lattice model proposed by Nakamura et $al.$[2] This model is introduced in the frustration of not only spin systems but also lattice systems, say "lattice frustration". The lattice frustration is new concept to discuss the structural phase transitions. Accordingly, RbCoBr$_3$ is a very unique compound with spin and lattice frustration, changing its spin and lattice alignments cooperatively to minimize the energy releasing frustrations. This study aims to understand the new spin-lattice cooperative phenomena in RbCoBr$_3$. The μSR measurements were performed at the RIKEN-RAL Muon Facility.

Figure 1 shows the ZF-μSR time spectra of RbCoBr$_3$. With decreasing temperature, the depolarization of muon spins becomes fast. Clear muon spin rotation was observed below the partial disordered phase transition temperature, $T_{N1} \sim 37$ K. Temperature dependence of the precession frequency obtained by Fourier analysis of the spectra is shown in Fig. 2. There are two branches below T_{N1}, one is the main component which can be observed down to low temperatures with the saturated frequency of about 4 MHz, and the other has higher frequency but broadens and seems to vanish below T_{N2}. The behavior of the main component, which is similar to the temperature dependence of the intensity of the ($\frac{1}{3}\frac{1}{3}$1) and ($\frac{2}{3}\frac{2}{3}$1) magnetic Bragg peaks,[1] indicates the development of a magnetic ordered state. The broadening of the higher component is possibly caused by smearing of the muon-spin rotation due to the pulsed muon-beam structure and/or due to the limitations of the time resolution of detecting system. This is because the frequency of this higher component is close to the resolution limit of the

RIKEN-RAL Muon Facility ($\sim$ 6 MHz) with decreasing temperature. However, we definitely confirmed through μSR experiments using a dc muon beam at PSI that the higher component was broadening with decreasing temperature. The broadening below T_{N2} is expected to be caused by the random domain structures due to a structural phase transition at T_{N2} suggested by the spin-lattice model.[2]
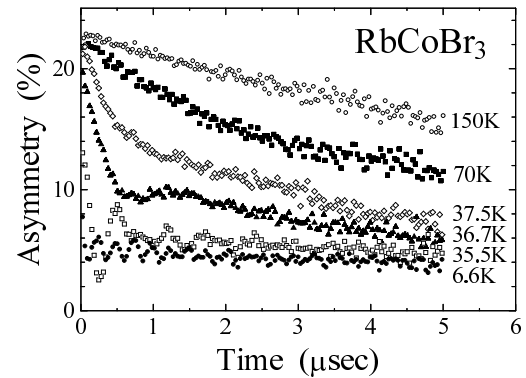
Fig. 1. ZF-μSR time spectra of RbCoBr$_3$.
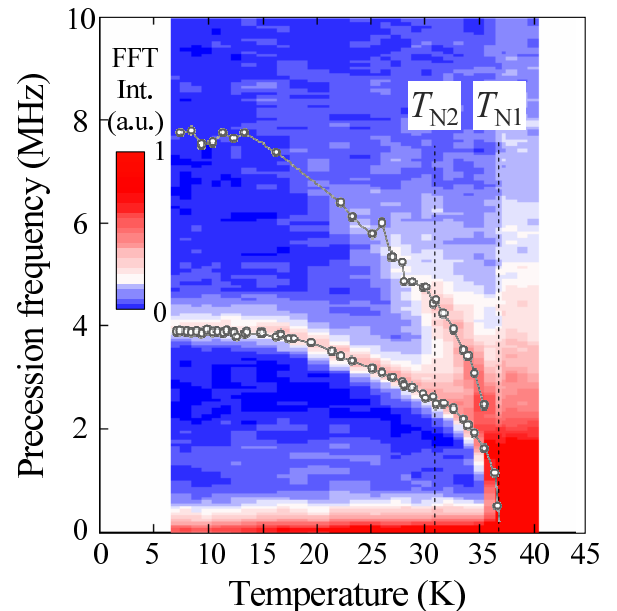
Fig. 2. Temperature dependence of the precession frequency obtained by Fourier analysis. Open circles indicate the peak center frequency.

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μSR studies on strongly correlated cubic Tm and Pr compounds with orbital degrees of freedom in the crystal-field ground state

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Cubic non-Kramers rare earth compounds of $TmAg_2In$ and $PrMg_3$ exhibit strongly correlated electron behavior characterized by a huge broad anomaly in T-dependence of the specific heat below 1 K[1]. The crystal field ground states (CFGS) in both have orbital degrees of freedom, invoking that multipoles in CFGS are possibly related to their strongly correlated electron behaviors. Especially, the non-Kramers CFGS doublet Γ_3 for $PrMg_3$ has no magnetic dipoles but electric quadrupoles and a magnetic octupole. In this study, we intend to clarify the ground state properties and the low energy dynamics at low-T by utilizing the μSR technique. μSR measurements were carried out using AUGUS spectrometer at RIKEN-RAL Muon Facility. The ZF and LF spin relaxation function $G_Z(t)$ was measured on the single crystals with the initial μ^+ spin polarization P_{μ^+} along the cubic [001] axis.

For $TmAg_2In$, $G_Z(t)$ at low-T was found to be fitted quite well by the two components exponential relaxation as $G_Z(t) = A_1 exp(-\lambda_1 t) + A_2 exp(-\lambda_2 t)$ with a ratio of $A_1 : A_2 = 2 : 1$ and $\lambda_1 \gg \lambda_2$. As shown in Fig. 1, λ_1 exhibits a strong T-dependence, while λ_2 is almost T-independent. At high-T, $\lambda_1 \approx \lambda_2$ and the two components are not well discriminated. Under LF, the exponential relaxation is found not to be decoupled easily indicating the electric origin of the relaxation. Most probable stopping sites are $(1/4, 1/4, 0)$ and its equivalent sites, which are the same as in the isomorphous compound of $SmAg_2In$ determined by TF μSR[2]. Recent specific heat measurement at ultra low-T has revealed a phase transition at $T_0 = 0.22$ K, suggesting that the increase of λ_1 down to the lowest-T of

our measurement reflects the slowing down of fluctuating moments toward T_0.

Fig. 2 shows ZF and LF $G_Z(t)$ in $PrMg_3$ at $T = 0.28$ K. In the case of the non-magnetic CFGS, the hyperfine coupling between the nucleus and the Van Vleck susceptibility introduces the enhancement of the local magnetic field from the nuclear magnetic moments at low-T[3]. As shown in Fig. 2, the experimental results can be described well up to LF of 200 Oe in terms of the dynamical Kubo-Toyabe (KT) model with two components, in which the local fields are *hyperfine-enhanced*. Here, the two components in $G_Z(t)$ are presumed on the analogy with the results of $TmAg_2In$ with the similar structure to $PrMg_3$. The *hyperfine-enhanced* factor used in the dynamical KT analysis is ~ 9, which is comparable with calculated one from the van Vleck term of $PrMg_3$ ($\cong 7$). These mean the possibility of indirectly deducing $1/T_1$ of ^{141}Pr nucleus from μSR. The fluctuation rate of the local field obtained by the dynamical KT analysis increases with decreasing-T at low-T. We may observe the slowing of the fluctuation of the quadrupole moments in 4f electrons through the ^{141}Pr nucleus, of which quadrupoles couple with those of 4f electrons. μSR studies to investigate lower-T for both compounds are proposed in the continuation proposal.
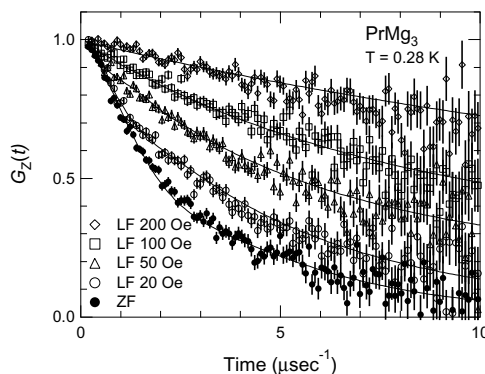
Fig. 2. ZF and LF depolarization of μ^+ in $PrMg_3$ at $T = 0.28K$. The solid lines denote the calculated results in terms of dynamical Kubo-Toyabe model.

Fig. 1. T-dependence of the zero-field μ^+ relaxation rate λ_1 and λ_2 in $TmAg_2In$.

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μSR study of heat transport due to spins in 2-leg spin-ladder system Ca$_9$La$_5$Cu$_{24}$O$_{41}$

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[μSR, heat transport due to spins]

In several low-dimensional quantum spin systems, it has been reported recently that the temperature dependence of the thermal conductivity exhibits anisotropic peaks or shoulders. In the 2-leg spin ladder system Ca$_9$La$_5$Cu$_{24}$O$_{41}$, for example, the temperature dependence of thermal conductivity along the c-axis parallel to the leg of the spin ladder exhibits a very large peak around 150 K.[1,2] Some argue that the large peak is attributable to the thermal conductivity due to magnetic excitations, namely, the thermal conductivity due to spins. This suggestion is only supported by a few studies of the anisotropy and nonmagnetic impurities effects of the thermal conductivity. Therefore, the anisotropic behaviors of the heat transport due to spins have not yet been directly proved. In this study, we try to detect the change in spin dynamics caused by heat transport due to spins on 2-leg spin-ladder systems Ca$_9$La$_5$Cu$_{24}$O$_{41}$ from μSR.

We performed the μSR experiments at the RIKEN-RAL Muon Facility at $T = 150$ K with and without a temperature difference, $\Delta T = 10$ K, along the c-axis. Three rectangular single-crystals of Ca$_9$La$_5$Cu$_{24}$O$_{41}$, with dimensions of ~ 1 mm thickness, ~ 10 mm width and ~ 30 mm length, were mounted on our own sample holder as shown in Fig. 1. One side of the single-crystals was set on a silver plate as a heat sink and the opposite side was set on a silver plate with chip resistances as heaters. The ΔT across the samples was measured with several Cernox thermometers.

The inset of Fig. 2 shows the typical μSR time spectra in the longitudinal fields (LF) up to 3950 G with and without ΔT along the c-axis. The time spectra in low fields up to a few tens G are driven by the fluctuation of the nuclear dipoles, because the initial part of the time spectra decays with a Gaussian-like function. On the other hand, it is expected that time spectra in high fields are affected by the fluctuation of the Cu-3d spins, because the internal field can not be decoupled even by a high LF of 3950 G. All of the time spectra were analyzed using the function $A_0 \exp(-\lambda t)G_{\mathrm{KT}}(t)$, where A_0 is the initial asymmetry, λ is the relaxation rate of the muon spin polarization and $G_{\mathrm{KT}}(t)$ is the static Kubo-Toyabe function.[3] The λ in low fields and high fields is expected to correspond to the fluctuating field created by the nuclear dipoles and the Cu-3d spins, respectively. Figure 2 shows the field dependence of λ with and without ΔT. The values of λ with and without ΔT are almost the same. This shows that

changes in the fluctuation of the Cu-3d spins due to heat transport are not detected by μSR. The possible reasons are: (1) fluctuation occurring too fast due to large exchange interaction, J, and/or (2) short mean free path of magnetic excitations due to diffusive heat transport in Ca$_9$La$_5$Cu$_{24}$O$_{41}$. For conclusive results, it will be nesessary to perform an experiment on a $S = 1/2$ antiferromagnetic spin system with small J, where the heat transport due to spins is ballistic.
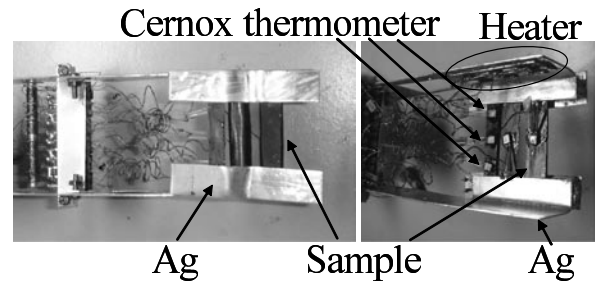
Fig. 1. Sample holder for measurements under temperature gradient.
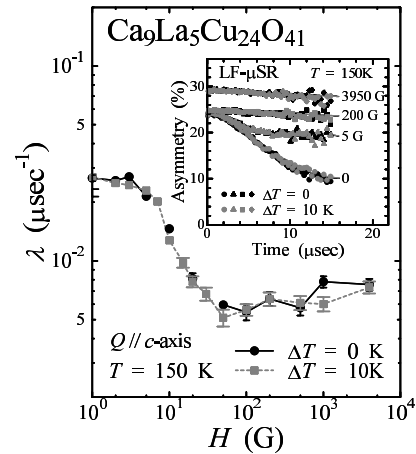
Fig. 2. Field dependence of relaxation rate, λ, with and without temperature difference, $\Delta T = 10$ K, at $T = 150$ K. Heat current, Q, flows along the c-axis. The inset shows the μSR time spectra of Ca$_9$La$_5$Cu$_{24}$O$_{41}$ under the longitudinal fields with and without ΔT at $T = 150$ K.

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μSR study of Heusler compounds $Ru_{2-x}Fe_xCrSi$

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Recently magnetic properties of the Heusler compounds $Ru_{2-x}Fe_xCrSi$ were studied.[1] It was found that the Fe-rich compounds are ferromagnetic. On the other hand the Ru-rich compounds with $x = 0.1$ were found not to be ferromagnetic but to show a peak in magnetic susceptibility at 30 K which is likely to indicate an antiferromagnetic transition. Meanwhile, no anomaly in resistivity and specific heat to indicate phase transition was found. Moreover below ~ 15 K separation of the magnetic susceptibility between zero-field cooling and field cooling process was found. This behavior suggests the appearance of a spin glass state. In order to clarify if a magnetic order develops or not, zero-field (ZF) μSR and longitudinal-field (LF) μSR measurements were performed for polycrystalline $Ru_{1.9}Fe_{0.1}CrSi$. The measurements were carried out at the RIKEN-RAL Muon Facility using a spin-polarized single-pulse positive surface muon beam. The time spectra, namely, the time evolution of the asymmetry parameters $A(t)$ was measured down to 4.3 K.

Figure 1 shows ZF-μSR time spectra of $Ru_{1.9}Fe_{0.1}CrSi$ at various temperatures. Spectra below 40 K appear to consist of two components and their $A(t)$ seem to be expressed as

$$A(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t), \qquad (1)$$

where A_i and λ_i $(\lambda_1 > \lambda_2)$ are initial asymmetry and

Fig. 2. Longitudinal field H_{LF} dependence of A_2 at 4.3 K. The best fit by formula (2) is shown by the solid line.

muon spin relaxation rate for each component, respectively. As shown in Fig. 1 the time spectra are fitted well by Eq. (1). With decreasing temperature the initial asymmetry $A(0)$ decreases and becomes smallest at ~ 16 K. This behavior suggests the developments of a static internal filed.

In order to examine if this behavior originates from a static internal field, LF-μSR measurements were carried out at 4.3 K under longitudinal magnetic field H_{LF} up to 3950 Oe. These time spectra are also well fitted by Eq. (1). The tail of the spectra increases with increasing H_{LF}. These results mean that the observed depolarization of muon spins is caused by a static internal magnetic field H_{int}. Figure 2 shows H_{LF} dependence of A_2 at 4.3 K. This represents the decouple of muon spins from H_{int} by H_{LF}. On the assumption that the magnitude of the internal field at each muon site is unique but its direction is random, H_{int} was estimated by the following formula:

$$A_2 = \frac{3}{4} - \frac{1}{4x^2} + \frac{(x^2-1)^2}{16x^3} \ln \frac{(x+1)^2}{(x-1)^2}, \qquad (2)$$

where $x = H_{LF}/H_{int}$. The solid line of Fig. 2 is the best fit of Eq. (2) and $H_{int} \sim 2100$ Oe was evaluated.

The present results shows the existence of a static internal field in $Ru_{1.9}Fe_{0.1}CrSi$ at low temperatures. This is consistent with observed remarkable irreversibility in the magnetic susceptibility below ~ 15 K, which indicates a spin glass state.

Fig. 1. ZF-μSR spectra of $Ru_{1.9}Fe_{0.1}CrSi$ at various temperatures. Solid lines are the fit of $A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t)$.

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Superconductivity in one-dimensional CuO double chains

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One of the most famous high-temperature superconductors discovered so far is $YBa_2Cu_3O_{7-\delta}$. When the Y-sites were replaced by different lanthanides, Pr alone showed neither superconductivity nor a metallic nature despite retaining a crystalline structure, whereas all the other elements showed superconducting transition temperatures of approximately 90 K. Thus, "Pr issues" were of particular interest in this research from the start.

The $Pr_2Ba_4Cu_7O_{15-\delta}$ (Pr247) compound has both CuO double chains and CuO single chains, and shows metallic conductivity at low temperatures due to metallic conduction in the CuO double chains. Recently, we found that Pr247 compounds show superconductivity below 18 K after a reduction process by post-annealing in a vacuum.[1,2] A nuclear quadrupole resonance experiment revealed that the superconductivity in Pr247 is realized at the CuO double-chain layers.[3] We performed μSR experiments on superconductive and non-superconductive samples of Pr247 to obtain information on the superconductivity on Pr247.
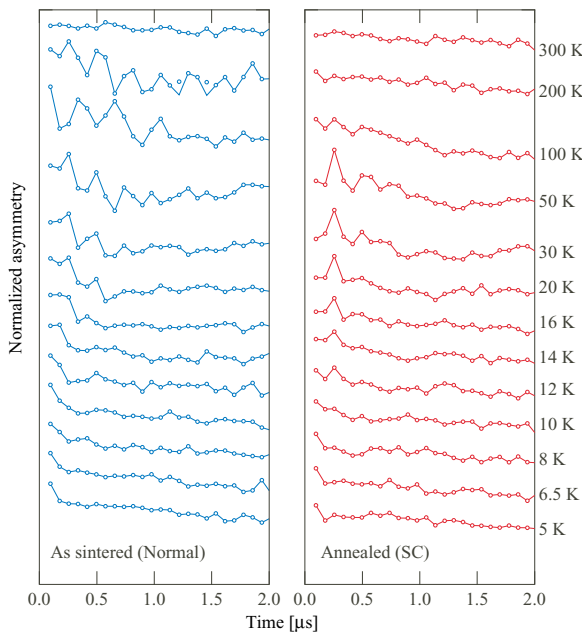
Fig. 1. Zero-field μSR spectra of the as-sintered and the annealed samples of Pr247.

The as-sintered sample examined in this study exhibits no superconductivity. We prepared an annealed sample by annealing the as-sintered sample for 72
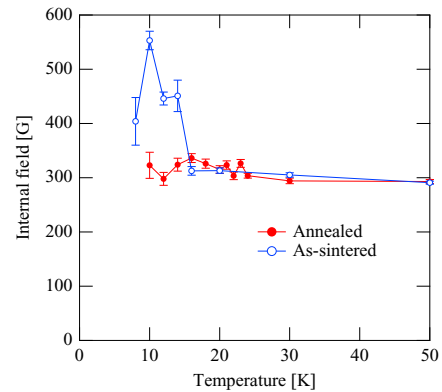
Fig. 2. Temperature dependence of the internal field in the as-sintered and the annealed Pr247 samples.

hours at 673 K in vacuum. The annealed sample with oxygen deficiency $\delta = 0.38$ has a superconducting temperature T_c of 22 K with the superconductive volume fraction of 60%. Figure 1 shows zero-field μSR spectra on as-sintered and annealed samples of Pr247. Muon spin rotation is observed in both samples. However, the rotation signal of the as-sintered sample, which shows no superconductivity, is somewhat larger than that of the superconductive annealed sample.

Temperature dependence of the internal field is shown in Fig. 2. Below 16 K, the internal field of the as-sintered sample increased rapidly, while that of the annealed sample exhibited only a small change. We also measured another superconductive annealed sample, which has $T_c = 14$ K with the superconducting volume fraction of 1.8%. In this sample, the profile of temperature dependence of the internal field is similar to that of the as-sintered sample. The increase in the internal field at low temperature is probably due to the magnetic ordering of Pr below the Néel temperature. These results indicate that suppression of the magnetic ordering of Pr has a close relationship with the appearance of superconductivity of Pr247.

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μSR study on ferromagnetism of rubidium clusters in zeolite A[†]

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Alkali metal nanoclusters can be generated in the periodically arrayed spaces of zeolite crystals. Magnetically ordered states have been found in these systems without any magnetic elements[1,2]. Recently, we have newly found ferromagnetic properties in Rb clusters in zeolite A[3]. The mechanism of ferromagnetism seems different from that of K clusters.

Zeolite A has the LTA-type framework structure as shown in Fig. 1, where the α and β cages with the respective inside diameters of $\simeq 11$ and $\simeq 7$ Å are alternatively arrayed in a CsCl structure. We used a highly Rb-exchanged zeolite A with chemical formula of $Rb_{11}K_1Al_{12}Si_{12}O_{48}$, where the host alkali cations (K^+, Rb^+) are distributed in the space of zeolite framework ($Al_{12}Si_{12}O_{48}$). By loading guest Rb atoms into dehydrated zeolites the $5s$-electrons of the adsorbed Rb atoms are shared among guest Rb^+ and host cations, and confined in the zeolite cages to form Rb clusters. Rb clusters show ferromagnetic properties at loading densities (the number of guest Rb atoms per formula unit), n, larger than 4.0[3]. At these high values of n, Rb clusters are in metallic state and clusters formed in both α and β cages[3]. The basic properties of Rb clusters are different from that of K clusters where the clusters are formed only in the α cages and the ferromagnetic property is explained by spin-canting of antiferromagnetism in an insulating state. For Rb clusters, a model of ferrimagnetism has been proposed[3]. In order to investigate the ferromagnetic properties in detail, we performed μSR measurements at RIKEN-RAL for Rb clusters in zeolite A with $n = 5.8$. This sample has the highest Curie temperature, $T_C \sim 5$ K.

The internal field is confirmed to be almost static in LF-μSR spectra below $\simeq 4$ K. At $T \le 6$ K, ZF-μSR spectra were fitted with a function sum of an exponential and a precession component

$$P(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t)\cos\omega t + B, \quad (1)$$

where A_1 and λ_1 are the relaxation amplitude and the muon spin depolarization rate of the exponential component, and A_2, λ_2 and ω are the the relaxation amplitude, the damping and the frequency of the muon spin precession component, respectively. The center and the distribution width of the internal field, B_{int} and ΔB_{int}, respectively, are estimated from ω and λ_2. Figure 2 shows temperature dependence of λ_1, B_{int} and ΔB_{int}. The exponential component dominates the decay, and the relaxation rate λ_1 obviously increases

at lower temperature, similar to that of spontaneous magnetization. At $T \sim 4$ K, $B_{int} \simeq \Delta B_{int}$ reflects the breakdown of magnetic ordered state near T_C. The ratio of the relaxation term to the total asymmetry, $(A_1+A_2)/(A_1+A_2+B)$, is estimated to be ~ 0.6. This value is high enough that the magnetic phase is in major part of the volume sample. K clusters in zeolite A are known to show very fast muon spin relaxation with an anomalous LF-dependence. This behavior is strongly related to the spin-canting mechanism. In the Rb clusters, however, such fast relaxation was not observed. This may indicate the different mechanism of ferromagnetism from that of K clusters.
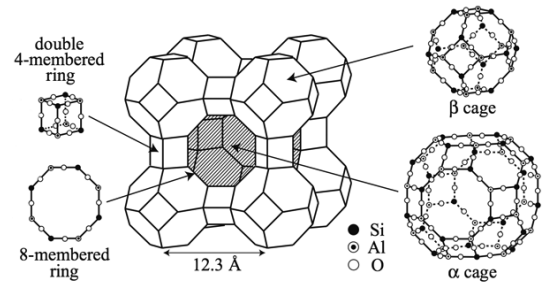
Fig. 1. Schematic illustration of the crystal structure of zeolite A.
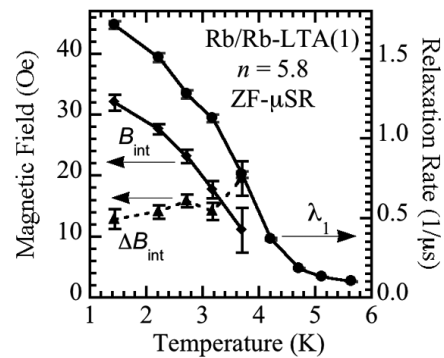
Fig. 2. Temperature dependence of muon spin relaxation rate, center and width of the internal field obtained from ZF-μSR for Rb clusters in zeolite A with $n = 5.8$.

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μSR Investigation of the Spin Dynamics of Central Fe Ions of Hemeproteins

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The main purpose of this study is to discover hints about relationships between the local structures of the central heme (Fe-protoporphyrin IX) and the functions of hemeproteins, which the largest single class of metalloproteins. Functions of hemeproteins are known to be not only to their 3D protein structures but also to the electronic state around their central Fe ions. In many cases, the electronic state of the central Fe ion is very sensitive to tiny changes in the surrounding protein environment. Thus, investigations of the electronic state of the central Fe ions from the microscopic viewpoint are quite important to understand functions of hemeproteins [1,2]. In order to simplify the study and avoid difficulties due to complexity of the protein environment, we have prepared Fe-porphyrin complexes as simple models of hemeproteins for the proposed μSR experiment.

In 2008, we obtained 6 days beam time at the ALC experimental area of the Paul-Scherrer Institut (PSI) in Switzerland to investigate the electronic states of the model-complexes of hemeproteins. This reports the results of the first attempt to investigate the electronic state of Fe(TPP)X (X= Imidazole, Cl) using high-field μSR measurements.

Figure 1 shows the samples prepared for the present μSR investitgation. Sample-(a) is Fe(TPP)(Imidazole)$_2$ (TPP=tetraphenylporphyrin) and sample-(b) is Fe(TPP)Cl. The difference between the samples is the local structure around Fe spin. That is, there is a difference in the number of molecules attached to the central Fe ion. Valence values of Fe ions in samples is Fe(III). We applied high-field μSR to these two model samples at room temperature up to 4.5 T using the ALC superconducting magnet in order to observe the dynamics of the Fe(III) ion.

Figure 2 shows high-field μSR time spectra of each model complex at room temperature. Under the zero-field condition, both samples showed strong depolarization behavior due to the strong fluctuations of Fe spins. As the field was increased up to the maximum of 4.5 T, the fast depolarization behavior recovered. The simple exponential function, $A_0 e^{-\lambda t}$, was applied to analyze time spectra. The solid lines in Fig. 2 are the best-fit results using this analysis function. Figure 3 shows the LF dependence of the depolarization rate, λ, of each sample. The λ tends to be suppressed with increasing LF above about 2 T and there seems to be a cut-off in λ near the maximum field of 4.5 T. In order to obtain more detailed information on the fluctuating internal field at the muon site, the Redfield function was applied to the field dependence of λ [3]. The solid lines in Fig. 3-(a) and (b) are the best-fit

results using the Redfield function. As shown in Fig. 3-(a) and (b), the internal field at the muon site which is coming from the fluctuating Fe spins was of the order of 2 kG and its frequency was around 400 MHz. Interestingly, no difference was observed in the values of the internal field at the muon site or its fluctuation rate. This means that the dynamics of the central Fe spin are not affected by the axial ligands.

We aplan to continue these measurements using other model samples which have different local structures and valence values of the central Fe spin in order to gather more information about the dynamics of the central Fe spin.
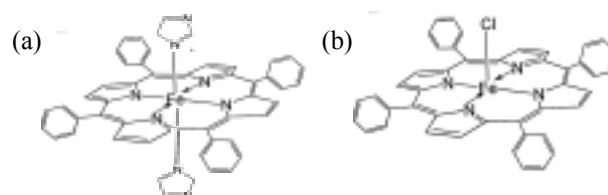
Figure 1: Model samples used in the current high-field μSR study; (a) is Fe(TPP)(Imidazole)$_2$ and (b) is Fe(TPP)Cl.
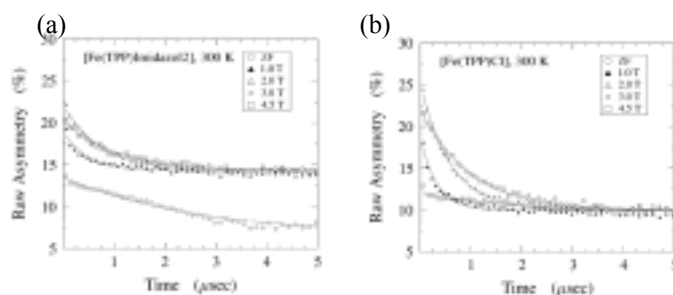
Figure 2: High-field μSR time spectra of (a) Fe(TPP)(Imidazole)$_2$ and (b) Fe(TPP)Cl obtained at various fields up to 4.5 T.
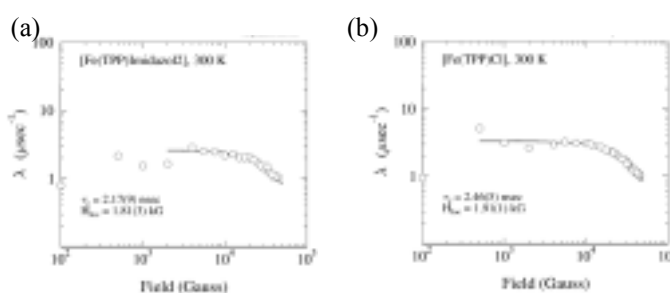
Figure 3: Field dependence of the dynamic muon-spin depolarization rate, λ, in (a) Fe(TPP)(Imidazole)$_2$ and (b) Fe(TPP)Cl. The solid lines are the best-fit results using the Redfield formula.

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Structural transition in Mo_3Sb_7 probed by muon spin relaxation[†]

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[structural transition, valence bond crystal, frustration]

A metallic compound Mo_3Sb_7, with the cubic Ir_3Ge_7 type structure (space group $Im\bar{3}m$), is a superconductor with a critical temperature $T_c \simeq 2.1$ K. The Mo sublattice ($12e$) is the 3D network of Mo-Mo dumbbells formed by nearest neighbors (NN). Next-nearest-neighbor (NNN) bonds form an octahedral cage at the body-centered position. The sufficiently short NN distance (3.0 Å) compared with the NNN distance (4.6 Å) makes us anticipate easy dimerization between NN pairs. Recently, Candolfi et al.[1] recognized Mo_3Sb_7 as an itinerant electron magnet and suggested the coexistence of superconductivity and spin fluctuations. Although no phase transition other than that at T_c was noticed in Ref. 1, Tran et al.[2] recently reported the presence of another phase transition at $T_S \simeq 50$ K, and proposed spin gap formation associated with Mo-Mo dimerization. Thus Mo_3Sb_7 is now classified as a new material with another phase transition prior to superconductivity. We have found clear evidence of the symmetry breakdown at T_S; a drastic change in the nuclear quadrupole resonance (NQR) spectrum and strong enhancement of the nuclear magnetic relaxation rates, $1/T_2$ and $1/T_1$[3]. X-ray analysis revealed that this is crystal symmetry transition from cubic to tetragonal[3].

To determine the magnetic state below T_S, we performed zero-field (ZF) and longitudinal-field (LF) μSR measurements at the RIKEN-RAL Muon Facility using a pulsed positive surface muon beam at 5–150 K under fields of 0 and 20 G[3,4]. We found no evidence of magnetic order, in accordance with the spin-singlet formation suggested in Ref. 2. The feature of ZF relaxation shows Gaussian-like depolarization both below and above T_S, as shown in the inset of Fig. 1. The width of the static field distribution Δ estimated by fitting the data to the commonly used damped Kubo-Toyabe (KT) function is sufficiently small of $\Delta/\gamma_\mu \sim 1$ G (γ_μ the muon gyromagnetic ratio), which is attributed to dipolar fields coming from randomly oriented nuclear spins. As seen in Fig. 1, with increasing temperature passing through T_S, the width of the field distribution Δ/γ_μ is reduced from $\sim$2.1 to $\sim$0.5 G via a thermal excitation process with activation energy of $E_a/k_B \simeq 120$ K. We interpreted this temperature dependence as the motional narrowing of the nuclear dipolar field associated with the lattice dynamics from
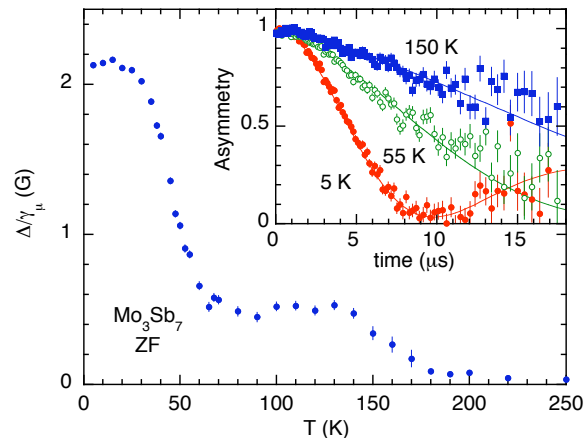
Fig. 1. T dependence of the ZF Kubo-Toyabe relaxation rate Δ in Mo_3Sb_7. Inset shows typical examples of ZF-μSR spectra. Solid curves indicate the fit by the damped KT function. (Cited from Ref. 3.)

tetragonal to cubic.

By applying LF, the Gaussian term is decoupled; the time evolution is roughly described by the single exponential functions as $P_\mu(t) = \exp(-\lambda t)$ where λ is the relaxation rate. The relaxation rate λ shows a divergent behavior at T_S, which is qualitatively same as that of the nuclear spin-lattice relaxation rate $1/T_1$ estimated in ^{121}Sb-NQR experiment[3], although the enhancement of NQR-$1/T_1$ at $\sim T_S$ looks much stronger. The critical behavior suggests that the phase transition is triggered by the instability in the Mo electronic system.

Thus, the temperature dependence of Δ estimated in ZF-μSR, corresponding to the nuclear spin-spin interaction, is relatively moderate and is attributed to the atomic motion in the three-dimensional crystal. On the other hand, the LF relaxation rate at $\sim T_S$ is dominated by the critical phenomenon probably in the electronic system. Taking account of these facts, we propose long-range order of spin-singlet dimers, i.e., the formation of the valence bond crystal below T_S, possibly due to the frustration of interdimer antiferromagnetic interaction.

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[†] Condensed from the articles in Refs. 3 and 4, and published in RIKEN Research
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Dynamics of Amorphous Polymers near Glass Transition by μSR

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We have studied the dynamics of two glass-forming polymers (polybutadiene (PB) and polyisobuylene (PIB)) in a temperature range from 10 to 300 K using μSR covering the glass transition temperature Tg. PB and PIB have molecular weight and polydispersity of Mw= 200,000, Mw/Mn=1.2 and Mw=800,000, Mw/Mn=2, respectively. The glass transition temperatures Tg are180 K and 200K, respectively. The μSR measurements were done at the RIKEN-RAL Muon Facility. The temperature range of the measurements was 10 to 300 K for both the samples.

Figure 1 shows decays of asymmetry for PB and PIB at 300 K under longitudinal magnetic field of 100 G. The decays of PB were described in a single exponential function in the temperature range examined while those of PIB showed an additional slow decay component at high temperatures above ~200K. At the moment the origin of the slow component is not clear. We analyzed the decays fitting a single exponential function to the data. In one fitting procedure all parameters were free, and in another procedure we assumed the intensity of asymmetry was independent of temperature. The temperature dependence

Figure 2. Temperature dependence of decay rate for PB. Solid curve was drawn by eye.

of the decay rate evaluated in both the procedures are shown in Figure 2 for PB. In the Figure, the open symbols show the results of the free parameter fits. The decay rate (or relaxation rate) begins to increase steeply with temperature above about the glass transition temperature Tg (~180K), showing that the glass transition is clearly observed in the μSR experiment. This agrees with the previously reported data by Pratt et al.[1]. In a temperature range below ~80 K the results of the two fitting procedures are very different. We see a maximum of the decay rate at around 40 K in the free parameter fits. However, when the amplitude of asymmetry is fixed, the decay rate monotonously increases with temperature. Judging from the previous data obtained by other methods such as inelastic neutron scattering [2], the monotonous increase in the decay rate is more physically reasonable. Hence, we employed the results obtained when the intensity of asymmetry was fixed. In the result the temperature dependence of the decay rate changes at around 100-120 K. This temperature corresponds to the onset temperature of the so-called pico-second fast process (Tf), which was revealed in inelastic neutron scattering [2]. This observation strongly suggests that we can detect polymer motion in pico-second order in μSR measurements as well as motion in micro-second at Tg.

Figure 1.   Decays of symmetry for PB and PIB at 100K.

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Muon spin rotation and relaxation on the one-dimensional cobalt(II)-radical coordination polymer magnet

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The first single-chain magnet [Co(hfac)$_2$•AnNN] was discovered by Gatteschi et al.[1] (see Fig. 1a with R = CH$_3$). The single-chain magnet nature is identified with magnetic hysteresis from a single-chain origin without any interchain interaction. On the other hand, we have reported the record coercivity (H_C = 52 kOe at 6 K) for [Co(hfac)$_2$•BPNN] (abbreviated hereafter as CoBPNN, R = n-C$_4$H$_9$).[2] The phase diagram of CoBPNN was empirically depicted as: a hard magnet for $T \leq 10$ K and a soft magnet for 10 K $< T \leq$ 45 K. Although a long-range order is likely to occur before it behaves as a hard magnet, no direct evidence for long-range order has yet been obtained, and the temperature at which the long-range order takes place still remains in question.

The μSR measurements on CoBPNN were carried out at the RIKEN-RAL Muon Facility in the UK. Fig. 1b shows the ZF-μSR of CoBPNN. Above 28 K, monotonically decreasing relaxation curves were obtained, which corresponds to a paramagnetic phase. Upon cooling, the signal became the superposition of slow and fast relaxing signals. Below 28 K, a few cycles were found for $t \leq 0.5$ μs. The appearance of oscillation due to the muon Larmor precession clearly indicates the presence of an appreciable internal magnetic field due to a spontaneous magnetization. The coherency of the rotation implies a magnetically ordered state. The small amplitude of the oscillation may be related with the size of the magnetic domain.
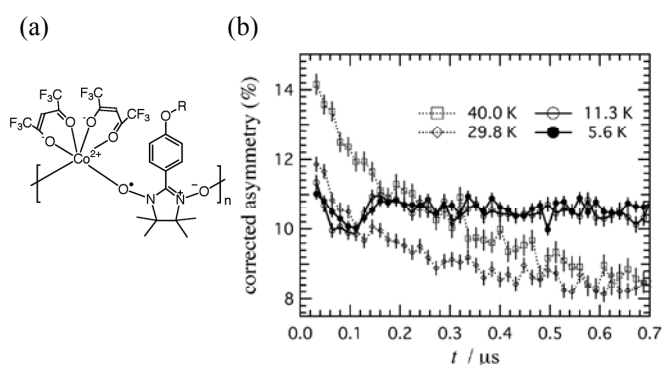
Fig. 1. (a) Structural formula of CoBPNN. (b) Temperature dependence of ZF-μSR time spectra on CoBPNN in a temperature range from 40 K to 5 K.

We investigated detailed muon-spin relaxation in a wide temperature range to clarify whether the long-range order would take place at 28 K or somewhere else. The time spectra below 90 K were analyzed based on the following equation consisting of two components, $A(t) = A_{fast}(0)\exp(-\lambda_{fast}t) + A_{slow}(0)\exp(-\lambda_{slow}t)$. The relaxation rate

constant (λ_{fast}) and the total initial asymmetry $A(0)$ are plotted as a function of temperature (Fig. 2). A sharp cusp of λ_{fast} was found at 40 K and a plateau of $A(0)$ below 40 K. An extremely slow decay and a constant $A(0)$ imply completely frozen systems such as magnetically ordered systems. The temperature at the λ divergence is usually defined as a magnetic transition temperature. In our previous report,[2] an apparent magnetic phase transition temperature of CoBPNN was estimated to be 45 K, which corresponds to 40 K in the present experiments. The present value is more reliable because the experiments were conducted at zero-field.
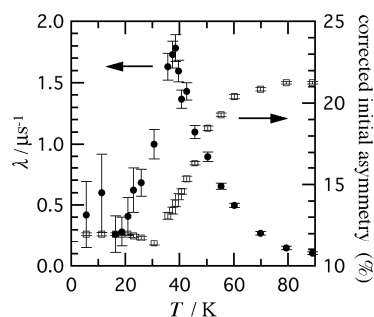
Fig. 2. Muon-spin relaxation in the ZF-μSR on CoBPNN. Temperature dependence for the rate constant λ_{fast} and total initial asymmetry $A(0)$ ($= A_{fast}(0) + A_{slow}(0)$).

Analysis according to the Arrhenius equation, $\ln(2\pi\nu) = -\ln(\tau_0) - E_a/k_BT$, gave E_a/k_B = 350 K and τ_0 = 6.8×10^{-13} s obtained from the ac susceptibility measurements whose time scale was 10^0 – 10^{-4} s.[2] The temperature at which the dynamic process is sufficiently slow that $\nu = 10^{-4}$ Hz (i.e., τ becomes hours) is 10 K from the extrapolation of this equation, which corresponds to the critical temperature for the hard magnet behavior. Similarly, if the dynamic process is assumed to be as fast as $\nu = 10^6$ Hz, the freezing temperature would rise to 28 K. This calculation perfectly agrees with the μSR results. The temperature of 10 or 28 K is not essential for the magnetic ground state. On cooling, the magnetic hardness gradually grows in a unique phase below 40 K, which can be defined as the intrinsic magnetic phase transition temperature.

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Gas-Pressurized μSR Setup at the RIKEN-RAL Muon Facility

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Pressure is an important parameter which allows the investigation of novel electronic states of solid-state materials. Since the muon-spin-relaxation (μSR) method can sense magnetic properties of materials in the zero-field (ZF) condition, the demand for a high-pressure μSR technique has been increasing recently in order to study magnetic properties and ground states of materials such as organic conductors and strongly correlated systems. The RIKEN-RAL Muon Facility is the only current facility which can provide a high-momentum double-pulsed muon beam up to 120 MeV/c.[1] Thus, the development of a high-pressure μSR setup for the RIKEN-RAL Muon Facility is very important in offering a new experimental technique to μSR users working in materials science. The RIKEN μSR team has been collaborating with the ISIS high-pressure group at the Rutherford Appleton Laboratory (RAL) since 2005 in the development of a gas-pressurized high-pressure μSR setup. A gas-pressurized setup has the particular advantage over a clamp cell design in being able to change the pressure continuously without any change in the other sample conditions. This report provides detailed information on the design and development of the high-pressure system.

We finished the assembly of a high-pressure cell, a high-pressure pump and an intensifier in April 2008 and tested the system at the RIKEN-RAL Muon Facility.[2] This is the first report on the test of the gas-pressurized system with a real muon beam at RAL. Designed values and photographs of each component have been reported already in the RIKEN Accel. Rep. Prog. Rep. 2006.[3] In order to confirm the signal-to-noise ratio (SN ratio) of the high-pressure set up, powdered Fe_2O_3 was mounted in the cell and measured at room temperature. Iron moments in Fe_2O_3 show an antiferromagnetically ordered state at room temperature. The appearance of a strong internal field at the muon site from the ordered iron moments causes the fast depolarization of the muon spin within the time resolution of the detecting system. Accordingly, the muon-spin asymmetry is lost when the injected muons stop in the Fe_2O_3 powder.

Figure 1 shows the momentum dependence of A_0, the muon-spin asymmetry at t=0, measured in a transverse field (TF) of 20 G. The high-pressure cell used for this test was made of CuBe and has a flat wall, 8 mm thick, for the injection of the muon beam. This cell can be used up to the maximum pressure of 6.4 kbar.[2,3] High-momentum backward-decay muons were tuned from 80 MeV/c to 100 MeV/c. Time spectra have been analyzed by using the function $A(t) = A_0 G(\Delta,t)\cos(\omega t+\phi)$ for the time evolution

of the precessing part of the muon-spin asymmetry, where $G(\Delta,t)$ is a Gaussian-shape damping factor of the muon-spin precession with a damping rate of Δ. The ω and ϕ are the frequency and phase of the muon-spin precession, respectively. The A_0 is about 25 % at 80 MeV/c and shows a sudden drop at around 89 MeV/c with increasing the muon momentum. The appearance of this sudden decrease of A_0 means that injected muons pass through the muon window and stop at the sample position. Using the Lorentz-type fitting function the position of the minimum point of the sudden dip was determined to be 88.9 MeV/c. The SN ratio was estimated from the depth of the dip of A_0 to be about 1:5. This means that about 1/6 of the injected muons stop at the sample position. Other signals come from the high-pressure cell. This SN value was not so bad and the signal from the sample was measurable. Thus, the current test using muon beams has proved that this system can be applied to real μSR at the RIKEN-RAL Muon Facility.

The asymmetry baseline decreases gradually with increasing momentum. The injected muons stop in deeper places of the cell when the momentum increases. In this case, the thickness of the wall of the cell seen from the muon toward the downstream side becomes thinner. Then, the absorption rate of positrons emitted from muons by the wall of the cell becomes smaller. This effect makes the total asymmetry smaller, because the backward-decay muon spin is directed to the downstream side of the muon path and the fraction of low-momentum positrons which have lower asymmetry increases at the forward counters located at the downstream side.
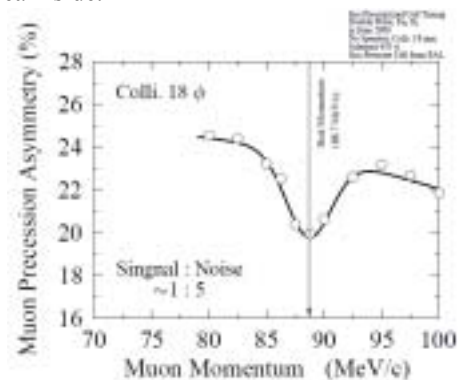
Fig. 1. Muon momentum dependence of the amplitude of the muon-spin precession in TF of 20 G measured at room temperature. The high-pressure cell was filled with Fe_2O_3.

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High pressure magnetic study on a molecular conductor, (DMe-DCNQI)$_2$Cu

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A series of anion radical salts, (DCNQI)$_2$Cu, where DCNQI is N,N-dicyanoquinonediimine, have been extensively investigated because of their peculiar physical phenomena such as heavy-fermion-like behavior and the Metal-Insulator transition[1]. The hybridization between the wide 1D $2p\pi$ bands and the narrow $3d$ bands is a key factor in understanding electronic properties of these systems. One of these salts, (DMe-DCNQI)$_2$Cu, (DMe-DCNQI = 2,5-dimethyl-DCNQI) has an unusual pressure-temperature (P-T) phase diagram (Fig. 1). At ambient pressure, this material shows metallic behavior down to 450 mK. Peculiar to (DMe-DCNQI)$_2$Cu, an insulating phase is induced by the application of pressure higher than 100 bar[2]. This unusual P-T phase diagram can be reproduced by the chemical pressure effect using selectively deuterated compounds[3]. The fully deuterated sample of (DMe-DCNQI)2Cu, in which the chemical pressure corresponds to 512 bar, exhibits the antiferromagnetic ordering below 8 K[4].

Recently, we have developed a high-pressure μSR setup for the RIKEN-RAL Muon Facility[5] and successfully observed a sign of pressure-induced magnetic ordering of (DMe-DCNQI)$_2$Cu, which was predicted by the chemical pressure study, using this high-pressure setup.

Figure 2 shows typical zero-field μSR time spectra at 500 bar. At a low-temperature of 2 K, significant decrease of initial asymmetry due to a static magnetic
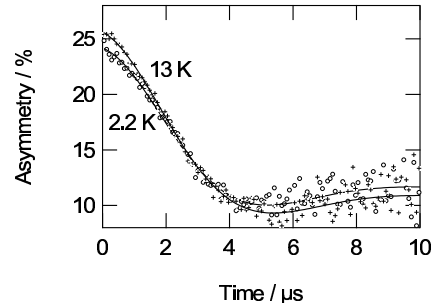
Fig. 2. Zero-field μSR time spectra of (DMe-DCNQI)$_2$Cu at 500 bar for selected temperatures.
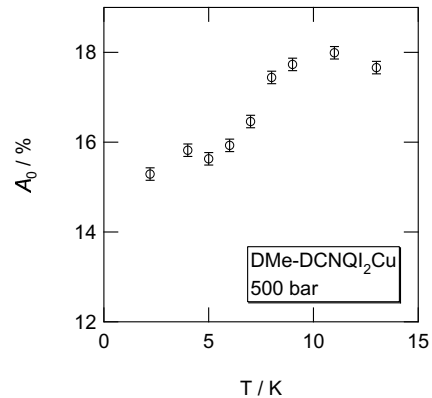
Fig. 3. Temperature dependence of a total relaxing A_0.

ordering is observed. The spectra are well fitted with a function: $P(t) = A_0 \exp(-\lambda t) \cdot G_{KT}(\Delta, t) + B$, where A_0 is a total relaxation, λ is a muon relaxation rate, $G_{KT}(\Delta, t)$ is Kubo-Toyabe function, Δ is the distribution width of the internal field due to the nuclear dipoles and B is temperature independent background. Temperature dependence of A_0 is shown in fig. 3. As shown in fig. 3, the decrease of A_0 is observed below 8 K, which indicates this compound is an antiferromagnet with $T_N = 8$ K. This T_N value is consistent with the chemical pressure study.

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Fig. 1. Pressure - Temperature phase diagrams of (DMe-DCNQI)$_2$Cu. The inset shows the magnification around the low-pressure region.

μSR Studies of Cyanide Bridged Magnets[†]

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Molecular magnets form a broad class of materials[1] that can often be engineered to have desired properties by careful chemical control. An example is the series of molecular magnets of the basic form $[M_A(L)_2]_3[M_B(CN)_6]_2$, abbeviated as $M_AM_B(L)$, in which the crystal structure is strongly influenced by the nature of the amine derivative ligands L[2], leading to a range of 1D, 2D and 3D magnetic structures. μSR investigations of the relationship between the critical properties and the structural arrangement of the constituents have been made for various examples of these molecular magnets at RIKEN-RAL and PSI. Some properties of the four cyanide-bridged magnets on which we report μSR results here are listed in Table 1. Example data plots for the critical behaviour of the first three materials are shown in Fig.1. The muon precession frequency $f(T)$ follows $f(T)/f(0) = t^\beta$ and the longitudinal muon spin relaxation rate $\lambda(T)$ follows $\lambda(T)/\lambda(0) = t^{-w}$, where $t = |T - T_c|/T_c$. From the measured critical behaviour the 3D ferromagnet NiFe(dipn)[3] is seen to conform reasonably well to the Heisenberg model, whereas the cubic ferrimagnet MnMn(dien) has a significantly lower w value reflecting its antiferromagnetic nature. NiFe(en) has an unusual highly anisotropic rope-ladder structure and is seen to have critical behaviour closer to the Ising model.

Fig. 1. Critical properties of some cyanide bridged magnets obtained from ZF μSR.

Table 1. The cyanide-bridged magnets studied here.

	S_A	S_B	T_c	Structure
NiFe(dipn)	1	1/2	8.5 K	3D network
MnMn(dien)	5/2	1	25 K	Cubic
NiFe(en)	1	1/2	12.5 K	Rope-ladder
MnMn(R,S-pn)	5/2	1	21 K	Layered

When L is a chiral ligand, non-collinear interactions may be enhanced and magnetic ordering and magnetic fluctuations with well-defined chirality may be possible. This was investigated for MnMn(L) where L is one of two chiral enantiomers R-pn and S-pn or a racemic 1:1 mixture of R-pn and S-pn (Rac-pn)[4]. The results for the ZF relaxation are shown in Fig.2 where a clear difference in behaviour is observed: in the racemic case the exponent w is found to be consistent with the N=2 non-collinear class, whereas in the chiral case a crossover to a weaker exponent is observed when T falls within 10% of T_c. Chiral spin correlations within the N=2 non-collinear class are expected to have the much weaker exponent $w = 0.10$, compared to $w = 0.4$

Fig. 2. Paramagnetic critical behaviour for MnMn(L) with racemic (L=Rac-pn) and chiral (L=R-pn,S-pn) ligands.

for normal spin correlations within the same class[5]. The data therefore suggest that such chiral spin correlations become dominant near the transition in the case of the chiral compounds.

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μSR study of structure dependent electron radical dynamics in polythiophene and its derivatives

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The study of electronic states of organic materials of conducting polymers is one of exciting fields of material science worldwide because of their novel electronic properties and their functional applications. Among the materials being intensively studied are polythiophene (PT) based polymers. Compared with other systems of conducting polymers, the polythiophene form an important class with certain practical advantages. These include : they are easily synthesized and doped with various dopants; they are chemically, thermally and environmentally stable in air and moisture both in doped and undoped states; they are easily modified by side change substitution for property modifications and they have potential commercial applications.

The most notable properties of these materials are their electrical conductivity resulting from the delocalization of electrons in the polymer backbone via doping to the conjugated π-orbital. These properties are related to the charge carrier transport and its mobility along (intra) and perpendicular (inter) to the polymer chain.

The macroscopic electronic transport measurement of conducting study conducted on PT reported that the functional properties of these polymers depend strongly on their structures such as regio-regularity (regio-random or regio-regular) and the side-chain length of its alkyl substituent. However, none of the reported studies can clearly explain the properties because of the mechanism of the intra- and inter-chain charge transport.

Here, we propose to study the microscopic intrinsic charge transport along the chain and perpendicular to the chain in polythiopene (PT) based polymers with different structures by a muon-spin-relaxation (μSR) method to elucidate the intra- and inter-chain hopping mechanism.

We have carried out longitudinal field (LF)- μSR measurements in a polythiophene sample of Poly(3-hexylthiophene-2,5-diyl) with regio-regular structure. All of the time spectra are well fitted by the two-component function below:

$$A(t) = A_1 exp(-\lambda_1 t) + A_2 exp(-\lambda_2 t) \qquad (1)$$

A_1 and A_2 are the initial asymmetries and λ_1 and λ_2 are the depolarization rates for fast and slow components, respectively. According to Butler *et al.*,[1] the LF dependence of the dynamical depolarization rate reflects the dimensionality of the diffusion of the spin-excited state. That is, the depolarization rate is proportional to $H^{-0.5}$ for 1 dimensional intra-chain diffusion and C-$H^{0.5}$ for 3 dimensional inter-chain diffusion.

Figure 1 shows the longitudinal-field (LF) dependence of the muon-spin depolarization rate (λ_1) of regio-regular polythiophene of Poly(3-hexylthiophene-2,5-diyl) at temperatures of 300 K and 10 K. The solid line is the best fit, using the diffusion model mentioned above. In low temperatures of 10 K, the depolarization rate reflected intra-chain diffusion, meaning that at low temperatures the charge transport is dominated by mobility along (intra) the polymer chain. With increasing temperature, the charge carrier mobility changes from intra-chain to an inter-chain diffusion one. Similar behaviors are also observed at an LF dependence of λ_2. However the values of λ_2 are two order magnitude smaller than that of λ_1 indicating that the contributions of the second component to the muon spin relaxation are very small compared to the first component. The present results indicate that the dimensional cross over is observed in the regio-regular polythiophene. Compared to other conducting polymers such as PANI and PPV[2], observation of dimensional cross over in the low temperatures indicated that the samples have more metallic behavior.

To obtain conclusive results, other polythiophene samples with different structures such as regio-random polythiophene and the polythiophene with different length of side groups should be used for the μSR measurements.

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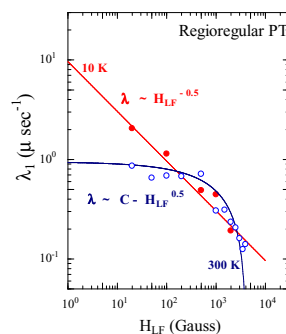
Fig. 1. The longitudinal-field dependence of λ_1 of regio-regular polythiophene (PT) of Poly(3-hexylthiophene-2,5-diyl) at 10 K and 300 K.

Lithium and muon diffusion in layered lithium-ion battery materials

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[muon, lithium-ion battery, diffusion]

Lithium cobalt dioxide $LiCoO_2$, in which the Li^+ plane is sandwiched by the two adjacent CoO_2 layers, has been extensively studied as a positive electrode material of lithium-ion batteries (LIB)[1]. In order to increase/optimize the performance of the LIB, fundamental electrochemical properties should be given for all the LIB materials. Among them, the Li diffusion constant (D_{Li}) plays a significant role on the battery performance. For non-magnetic compounds, D_{Li} is usually determined by ^7Li-NMR. However, for the positive electrode material such as $LiCoO_2$[2] and $LiMn_2O_4$[3], since the spin-lattice relaxation rate of ^7Li-NMR is strongly affected by the $3d$ electron-spins, it is difficult to estimate the correct D_{Li} by ^7Li-NMR. Therefore, we have carried out the μSR experiments in order to examine the D_{Li} for the LIB materials.

Powder samples of Li_xCoO_2 were prepared by an electrochemical reaction between Li and $LiCoO_2$ in non-aqueous Li-ion cells. According to an ICP-AES analysis, the Li/Co ratios of the samples were determined to be 0.73 and 0.53. For the μSR experiments, powder samples were packed in a sealed aluminum sample cell in a He-filled glove-box, and then placed on a copper sample holder in a cryostat. The μSR spectra were measured in the surface muon beam line of the RIKEN-RAL Muon Facility at the ISIS.

The μSR spectra above 50 K for the Li_xCoO_2 samples with $x = 0.73$ and 0.53 were well fitted by a dynamic Kubo-Toyabe function G^{DGKT};

$$A_0 P_{ZF}(t) = A_{KT} G^{DGKT}(t, \Delta, \nu) \exp(-\lambda_{KT} t) + A_{BG}, \quad (1)$$

where A_0 is the empirical maximum muon decay asymmetry, A_{KT} and λ_{KT} are the asymmetry and relaxation rate of the Kubo-Toyabe signal, Δ is the static width of the local frequencies at the disordered sites, and ν is the field fluctuation rate. As T increases from 50 K, Δ for the both samples decreases monotonically up to 160 K, and then rapidly drops around 170 K [Fig. 1(a)]. The $\nu(T)$ curves indicate an Arrhenius behavior in the T range between 170 and 320 K [Fig. 1(b)]. Although there are no magnetic transitions above 100 K by our previous μSR for Li_xCoO_2, the $\chi(T)$ curves show a small anomaly around 160 K [Fig. 1(c)]. Furthermore, electrostatic potential calculations suggested that μ are not located at the vacant Li site but at the vicinity of O_2^- ions. The increase in ν

above 150 K is, therefore, most unlikely due to μ diffusion but is likely due to Li^+ diffusion. In other words, ν corresponds to the jumping rate of Li^+ ions. The self-diffusion coefficient D_{Li}^{self} is, therefore, estimated by a simple random walk model; $D_{Li}^{self} = NZs^2\nu$, where N is the number of Li sites, Z the vacancy fraction, and s the jump distance. Using the jump distance of ~ 0.2 nm (the nearest distance between Li-Li ions, i.e. lattice parameter of a_h), D_{Li}^{self} is estimated to be about 10^{-10} cm^2s^{-1} at 250 K. This value is larger by two order of magnitude than that from the ^7Li-NMR and is comparable with that of electrochemical measurement[4].
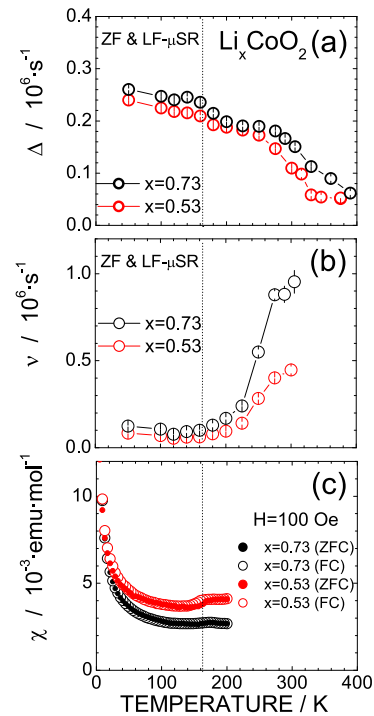
Fig. 1. Temperature dependences of (a) field distribution width (Δ), (b) field fluctuation rate (ν), and (c) susceptibility (χ) measured in the zero field-cooling (ZFC) and field-cooling (FC) mode with $H = 100$ Oe, for the Li_xCoO_2 with $x = 0.73$ and 0.53.

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Proton conductor II[†]

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[Proton diffusion, fuel cell]

Perfluorinated sulfonic acid copolymers (F-polymers) such as Nafion are currently being used as an electrolyte for vehicle fuel cells (FC). However, these FC do not work above 373 K (100°C) because Nafion is sufficiently conductive only when it contains enough water. Therefore, we need to develop a new electrolyte with high proton conductivity which does not use water, in order to improve FC performance. In our previous μSR experiments, we measured several F-polymers with various sulfonic acid densities (D_s).[1,2] The result suggested that μ^+s diffuse by thermally activated process, and their activation energy (E_a) decreases with increasing D_s. In other words, higher D_s result in lower E_a; that is, an F-polymer which works under dry conditions can be realized if we increase D_s above the critical value $(D_c = 4.47 \times 10^{-3}$ eq/cm$^3)$. Here, D_c is defined as the value at which $E_a = 0$. Unfortunately, it is difficult to synthesize F-polymers with $D_s \geq D_c$. Among several proton-conducting polymers, a hydrocarbon (HC) -polymer is one candidate for an FC electrolyte. Here, we report μ^+SR results on the HC-polymer to study the relationship between proton conducting behavior and D_s.

HC-polymer films based on sulfonated poly ether ether keton (PEEK) were dried in an Ar-filled globebox at 110°C for 12 hours. Then the several films with ~ 24 mm diameter were stacked in a sealed sample cell made of titanium with a gold o-ring at Toyota CRDL, and then the cell was transferred to the UK and set onto the oven sample holder. The μ^+SR experiment was carried out on the ARGUS surface muon beamline at the RIKEN Muon Facility at ISIS in the temperature range between 300 and 500 K.

According to the longitudinal field (LF) -μSR measurements, it was found that 70 $\sim$ 80% of μ^+ produce muonium. But the remaining 20 $\sim$ 30% provided an exponentially relaxing signal in zero external field (ZF), which is thought to be caused by μ^+ diffusion between the nearest neighboring SO$_3$ groups. Therefore, the ZF-μSR spectrum was fitted with the following equation;

$$A_0 P_{ZF}(t) = A_{fast} \exp(-\lambda_{fast} t) + A_{slow} \exp(-\lambda_{slow} t), \qquad (1)$$

where A_0 is the empirical maximum muon decay asymmetry, A_{fast} and A_{slow} are the asymmetries associated with the two components, and λ_{fast} and λ_{slow} are their relaxation rates. In Eq. (1), the first term corresponds to the signal from muonium, while the second term corresponds to the signal from μ^+ diffusion. Typical λ_{fast} and λ_{slow} values were 6 $\sim$ 7 (10^6 s^{-1}) and 0.05 $\sim$ 0.16 (10^6 s^{-1}), respectively. λ_{fast} has no temperature (T) dependency within the error bar, favoring production of muonium. The T dependence of λ_{slow} is found to obey the Arrhenius law described by Eq. (2) above 300 K, indicating the existence of a thermally activated process, as in the case for the F-polymer.

$$\lambda_{slow} = A \exp\left(-\frac{E_a}{kT}\right) \qquad (2)$$

where A, E_a and k are the pre-exponential factor, activation energy and Boltzmann constant, respectively. The D_s dependence of E_a is shown in Fig. 1. E_a for the HC-polymer decreases systematically with increasing D_s. This is very reasonable due to the fact that the average hopping distance shortens with increasing D_s. Interestingly, when D_s is same, E_a for the HC-polymer is almost half the E_a of the F-polymer. Furthermore, the D_c of HC-polymer is estimated to be 3.04×10^{-3} eq/cm^3 which is lower than that of F-polymer. This suggests that HC-polymers may be a better material for a proton conducting electrolyte without water.

Fig. 1. Relationship between D_s and activation energy E_a for HC- and F-polymers. The dashed lines calculated by the least square method. D_c is defined as the crossing point of the horizontal axis and dashed line.

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Muon transfer studies in solid D$_2$ with implanted alkali and alkaline-earth ions

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[Muonic atom spectroscopy, solid hydrogen film, ion implantation]

We have proposed the cold hydrogen film method [1] to expand muonic atom spectroscopy by utilizing nuclear beams, including, in the future, radioactive isotope (RI) beams, to produce radioactive muonic atoms. This method will enable the study of unstable nuclei by the muonic X-ray method at facilities where both intense μ^- and RI beams will be available. The basic concept is to stop both μ^- and nuclear beams simultaneously in a solid hydrogen film, followed by the application of the direct muon transfer reaction to higher Z nuclei to form radioactive muonic atoms. An experimental program to perform muonic X-ray spectroscopy with stable ions implanted in a solid hydrogen (H$_2$/D$_2$) film has been initiated at the RIKEN-RAL muon facility.

Promising results have already been reported from the first transfer experiment performed with isotopically separated ^{88}Sr and ^{86}Sr ions using a new surface ion source constructed and installed on the existing μA* apparatus with the aim of using radioactive isotopes in the future.[2] It can produce ions from alkali and alkaline-earth elements with high efficiency.

Last year we conducted further experiments and measured a target with isotopically separated ^{87}Sr ions. We utilized the same procedure as that used previously to implant argon and strontium ions. Figure 1 shows the delayed energy spectrum measured by the Ge detector with 1-mm pure D$_2$ and ^{87}Sr (solid line) ions implanted non-uniformly. The fitting curves obtained previously with ^{88}Sr (dotted line) and ^{86}Sr (dashed line) are also shown. A preliminary analysis shows that the measured isotope shifts are consistent with those observed in previous experiments using enriched strontium isotopes in very large quantities. This experiment was performed using natural strontium oxide (SrO) in the ion source, and only about 4×10^{16} ions of ^{87}Sr ions in the target. The set of measurements with strontium isotope ions is now completed. The data are being analyzed, and a publication should follow shortly.

The first measurement with barium isotopes was also performed with isotopically separated ^{138}Ba ions implanted into 1-mm thick solid deuterium film in a way similar to that used with strontium isotopes. Trans-
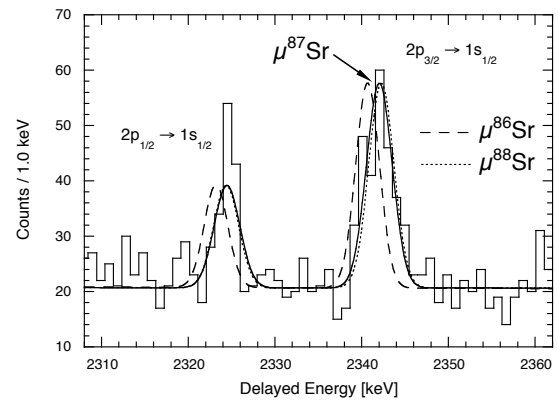
Fig. 1. Muonic ^{87}Sr delayed energy spectrum (solid line). Fitting curves for μ^{88}Sr (dotted line) and μ^{86}Sr (dashed line) measured previously are also shown.
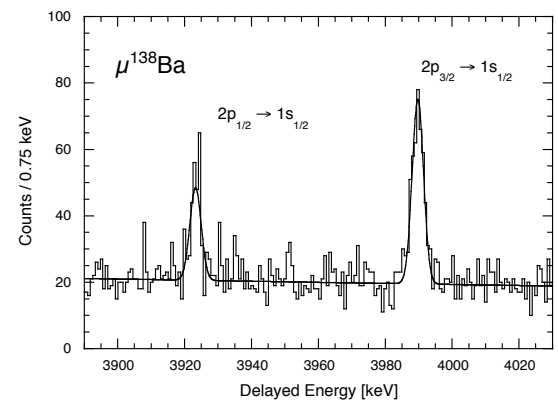
Fig. 2. Muonic ^{138}Ba delayed energy spectrum.

fer X-rays were successfully observed at around 4 MeV (see Fig. 2). The energies of muonic X-rays increase rapidly with the atomic number resulting in low detection efficiency. Our measurements are consistent with previous experiments performed using enriched Ba isotopes. The energy calibration is determined from muonic Pb X-rays at around 6 MeV measured in a separate run.

These experiments are still performed with a relatively large number of implanted ions because of the relatively low μ^- beam intensity at a momentum of 27 MeV/c. Future muon facilities with higher muon flux would require fewer implanted ions. Further measurements are planned with rare-earth elements.

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Feasible study of molecular effects on the muon transfer process

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and A. Shinohara[*1]

It is known that the muon capture phenomenon is influenced by the electron structure of a muon capturing molecule or atom when a free muon is captured on a muon atomic orbit directly. Our group has been studying on the molecular effects on the formation process of muonic atoms.

In this study, we focused on another muonic atom formation process; the muon transfer process. A muonic hydrogen atom (μ^-p) has a neutron-like property because of its small muon atomic orbit. So, it can penetrate the electron clouds of other atoms and the atomic muon then transfers to the deeper atomic muon level of the atom. This phenomenon is known as a "muon transfer process". In a muon transfer process, no molecular effects have been reported. We expect that some effects from valence electrons and/or molecular structure also exist in the muon transfer process because the size of muonic hydrogen is much larger than that of a neutron and the muon is transferred to an excited (i.e., large) muon atomic orbit.

We are going to study the molecular effects on the muon transfer process from muonic X-ray measurements for various molecules. If there are some influences on the muon transfer reaction from the electron structures of muon capturing molecules, different muonic X-ray spectra will be obtained from two samples that contain the same elements but have different molecular structures. We constructed a new system for muonic X-ray measurement (Fig. 1) at port-1 in RIKEN-RAL[1]. The feasibility of X-ray measurement was studied with argon, hydrogen and mixture of these gases under the pulsed muon beam conditions.

First, the optimum measuring conditions; muon momentum, beamline magnet current, beam slits, the magnetic field in target position, sample gas pressures (10 or 30 bar) and the configuration of radiation shield, were studied by using argon gas samples. Muonic X-ray measurements for pure argon samples were carried out under the optimized measuring conditions, to obtain the muonic X-ray spectra for the direct muon capture process. We also determined optimum muon irradiation momentum for mixed gases (hydrogen 99.7% and argon 0.3%) by using pure hydrogen gas samples, and then carried out muonic X-ray measurements for the mixed gas samples. The obtained X-ray spectra for argon and mixed gas samples are shown in Fig 2. Obvious differences in X-ray spectra were found. For example, the ratio of μAr(3-1) to μAr(2-1) X-ray

intensity in a mixed gas sample (0.19 ± 0.05) is larger than that in a pure argon sample (0.05 ± 0.01). In the mixed gas samples, muonic argon X-rays were mainly detected in a time region delayed from the muon beam pulse because the transfer process occurs after muonic hydrogen formation. We determined the lifetime of muonic hydrogen atoms experimentally from timing spectra of muonic argon X-rays (170 ± 130 ns for 10 bar and 90 ± 60 ns for 30 bar). These X-ray intensities and lifetimes reproduce the results of PSI experiment well[2].

In this study, we successfully obtained muonic X-ray spectra from muonic argon formed through a muon transfer process for 10 and 30 bar conditions. As the next step, we are planning to construct further effective systems (for example, by using more X-ray detectors) and use molecular gas samples for muon irradiations to examine the molecular effects on the muon transfer process
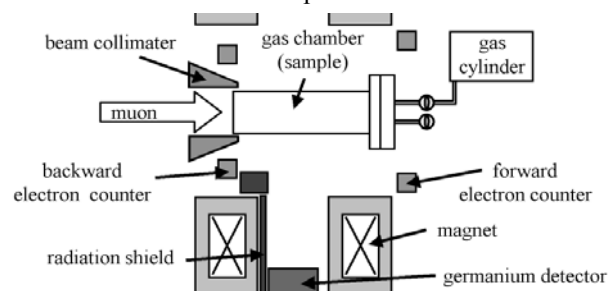
Fig. 1. Schematic view of the measuring system at port-1.
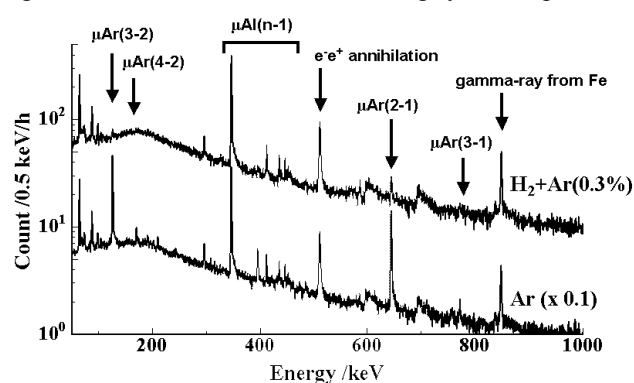
Fig. 2. Muonic X-ray spectra for Ar and H_2+Ar in 10 bar. The numbers in parenthesis represents the change in the muon principal quantum number. The sample chambers were made of aluminum and stainless steel. As a result muonic aluminum X-rays and gamma-rays from iron were also detected.

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Muon beam density enhancement effect with tapered tubes

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Charged particles can be effectively focused by a tapered glass tube, which deflects them at the inner wall surface and guides them to its outlet. Previous experiments confirmed this effect with a glass capillary for 2 MeV He$^+$ ions[1]) and for 8 keV Ar^{8+} ions[2]). Our recent experiment[3]) at RIKEN-RAL showed that a beam density of 54 MeV/c muons can be increased almost by a factor of two, when a tapered glass tube is inserted coaxially along the muon beam. This can be explained by a Coulomb scattering on the inner wall. This observation suggests a possibility exists to increase the number of available muons by optimizing the inner shape of collimators. For the practical application of μSR and other muon studies, detailed study of the density enhancement mechanism was performed using a continuous muon beam at TRIUMF, Canada.

The present experiment aims to understand two issues. One is to examine kinematics, such as kinetic energy distribution and angular distribution of the outcoming beam through tapered tubes, although at RIKEN-RAL, only the number of outcoming muons was measured due to the pulsed nature of the muon beam. The other is to observe the material dependence of the enhancement effects. Because of the larger reflection coefficient of the Coulomb scattering in a heavy material, Monte Carlo simulation shows that tapered tubes made of heavy materials, such as copper and gold, give larger density enhancement than glass tube. For simplicity, 1-dimensional scattering effects were measured using glass, Cu and Au-coated Cu plates rather than their tubes.

Figure 1 shows a schematic view of the setup at the M9B beam line, TRIUMF. All components are placed in a vacuum chamber so that low energy muons around 40 MeV/c cannot scatter or stop in the air. The incoming muon is identified by a 0.5 mm thick plastic scintillator (S1). A pair of vertical plates at a slightly narrowing angle are mounted around the beam axis, where some muons are scattered downstream, resulting in the beam being focused on a detector position. Muons stopped at the plates decay into positrons, which are identified by 5 mm thick plastic scintillators (S2-S7) surrounding the plates. The outcoming muon energy is measured by a 5mm thick and 16 mmϕ lithium drifted silicon detector (SSD, ORTEC TL-045-200-5). Plastic scintillators (S8, S9) are surrounded to monitor decay positrons which come from muons stopped in SSD. Angular dependence of the muon energy distri-
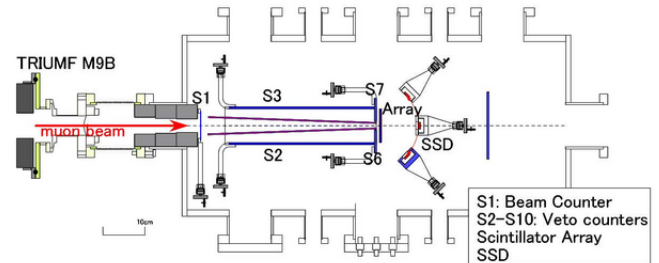
Fig. 1. A schematic view of the setup at M9B beam line.
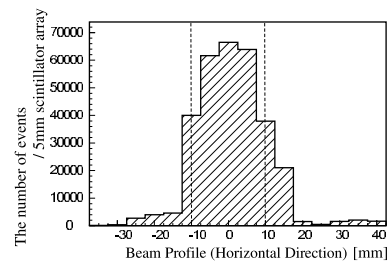
Fig. 2. A beam profile observed by the array counter of 5 mm segments, which is set 100 mm downstream of the plates outlet. The dashed line shows the outlet width.

bution is observed by SSD rotated around the outlet of plates. Angular dependence of the number of muons is observed by an array counter instead of SSD. It consists of 16 scintillators of 10 mm length and 5 mm square aligned in the vertical direction, and covers 10 × 80 mm^2 area in total. The SSD or array is mounted 10 mm or 100 mm downstream of the outlet. The 5 mm thick large plastic scintillator (S10) is mounted downstream to identify muons which do not stop at SSD, array or any counters.

Figure 2 shows a preliminary result of the beam profile observed by the array counter set 100 mm downstream of the outlet when the Cu plates are placed at the center. It shows that most muons are focused at the outlet although some muons are scattered wider than the outlet width of 20 mm.

In summary, we performed the test experiment to observe beam density enhancement with various tapered plates made of metals and glass instead of the tapered glass tube. Accumulated data in the last beam time is being analyzed at present. The next beam time is scheduled in June in order to complete this measurement.

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3.   Radiochemistry and Nuclear Chemistry

Precision measurement of the half-life of ^{90m}Nb using a gas-jet transport system

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The goal of our research is to clarify the effects of chemical structure on the decay constant of ^{90m}Nb. Almost all ^{90m}Nb nuclides decay via a 2.3-keV transition from the 124.7-keV level to the 122.4-keV level in ^{90}Nb.[1] Because of the high internal conversion coefficient and low transition energy, the probability of the transition is expected to vary with changes in the chemical structure affecting the electron density at the nucleus.

In the previous studies, the decay constant of ^{90m}Nb was obtained with a radioactive equilibrium method[2] or direct half-life measurement.[3] However, it appears that strong activity from undesired nuclear reaction products interfered with the measurements. In order to precisely determine the short half-lives of ^{90m}Nb in various chemical states, we employed an on-line gas-jet transport system in this study.

The isotope ^{90m}Nb was produced in the nuclear reaction ^{nat}Zr(p, xn)^{90m}Nb with a 14 MeV proton beam delivered from the RIKEN K70 AVF Cyclotron. Five ^{nat}ZrO$_2$ targets of about 100 μg cm^{-2} thickness were prepared by electrodeposition onto an 810 μg cm^{-2} aluminum backing foil. The targets were placed in a gas-jet chamber at intervals of 8 mm. The beam intensity was about 8 μA. The 14 MeV proton beam entered the target stack at an energy of 13.8 MeV. The reaction products recoiling out of the targets were stopped in the helium gas, attached to KCl aerosol particles generated by sublimation of KCl powder at 640 °C, and continuously transported to the chemistry laboratory.

The reaction products were collected on a glass filter for 180 s and assayed by γ-ray spectrometry with a HP-Ge semiconductor detector. The accumulation of γ-ray spectrum for 1 min was started 1 min after the end of aerosol collection and then repeated 30 times successively. Next, the reaction products were deposited on a polyethylene terephthalate film to measure the half-life of ^{90m}Nb in 20 M HF. After deposition for 30 s, they were dissolved in 20 M HF and subjected to γ-ray spectrometry. The accumulation of γ-ray spectrum for 6 s was started within 1 min after the end of the aerosol deposition and then repeated 15 times successively. In order to achieve adequate statistical precision, the procedure was repeated 120 times. The half-lives of ^{90m}Nb were determined by the reference source method[4] using ^{137}Cs as a reference source.

A γ-ray spectrum measured for 5 min after the 180-s aerosol collection is shown in Fig. 1. The γ peaks of ^{90g}Nb ($T_{1/2}$ = 14.6 h), ^{90m}Nb, ^{52m}Mn (21.1 min), ^{54m}Co (1.48 min), ^{64}Ga (2.63 min), and ^{91m}Y (49.7 min) are observed in the spectrum. The γ-peak of ^{90m}Nb at 122 keV is clearly separated from the peak of ^{90g}Nb at 133 keV, which is the closest to that of ^{90m}Nb. No serious background was observed in the γ-ray spectrum for determination of the half-life of ^{90m}Nb.

In the latter experiment, the γ peaks derived from the nuclear reaction products were observed only for ^{90m,g}Nb except for the 511-keV line. The obtained half-life of ^{90m}Nb in 20 M HF solution was 18.97 $\pm$ 0.03 s, which is consistent with the literature value [1] (18.81 $\pm$ 0.06 s) within 2σ. Although thoroughly corrections for dead-time and pile-up have not yet been performed, measurements under the low-background condition with good precision were conducted. The present system will allow us to measure the half-life of ^{90m}Nb with various chemical states.
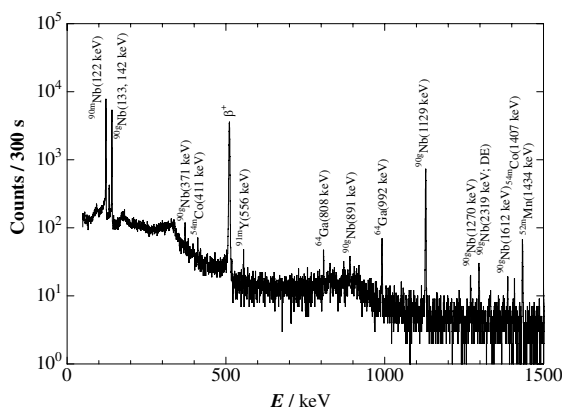
Fig. 1. Gamma-ray spectrum measured for 300 s after 180-s aerosol collection.

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Biodistribution of Riken multitracer (MT) and MT-EDTMP, MT-DOTMP in mice

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In nuclear medicine, samarium-153 labelled ethylene-diamine-tetramethylene phosphonic acid (EDTMP) and holumium-166 labelled 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetramethylene phosphonic acid (DOTMP) have been used, respectively, in bone pain palliation for bone metastases[1] and myeloablative treatment for multiple myeloma.[2] Both phosphonates typically accumulate in bone. The usage of these radiolabelled phosphonates is dependent on the half-life, radiation energy, and decay mode of selected nuclides. In order to examine the practical applicability of labelled phosphonates, it is important to investigate their metabolism. The Riken multitracer (MT) technique is highly efficient for comparison of many tracers under same conditions, and has been used to investigate the biodistribution of MT, MT labelled EDTMP and DOTMP in vivo.

Male 8-week-old ICR mice were grouped and administered with MT (in saline solution), MT-EDTMP, and MT-DOTMP. The blood, liver, kidney, small intestine, large intestine, femur, and brain were excised and weighed. The uptake rates of several nuclides (^{57}Co, ^{65}Zn, ^{75}Se, ^{83}Rb, ^{88}Zr, ^{88}Y, ^{101}Rh) in tissues were determined by gamma-ray spectrometry.

In this study, the seven radionuclides in MT were used to determine the biodistribution of MT chelated with phosphonates in seven representative tissues. The MT were distributed in various tissues and showed a specific accumulation pattern for each chemical species. Figure 1 shows biodistribution of ^{83}Rb chloride, ^{83}Rb-EDTMP, ^{83}Rb-DOTMP, ^{88}Zr chloride, ^{88}Zr-EDTMP, ^{88}Zr-DOTMP in mice. In the case of MT-EDTMP and MT-DOTMP, most of the MT- phosphonates accumulated in bone except for ^{75}Se and ^{83}Rb phosphonates. Yttrium-88 and ^{88}Zr phosphonates showed particularly high uptakes in bone compared to other tissues. Zirconium-88 phosphonates also showed fast bone uptake and rapid clearance from other soft tissues. The biodistribution of ^{75}Se phosphonates, and ^{83}Rb phosphonates showed the same behavior as ^{75}Se chloride and ^{83}Rb chloride, respectively. This suggests that Se and Rb exist in free ion form rather than as a phosphonate complex in vivo. In conclusion, these results should provide useful information for nuclear medicine.

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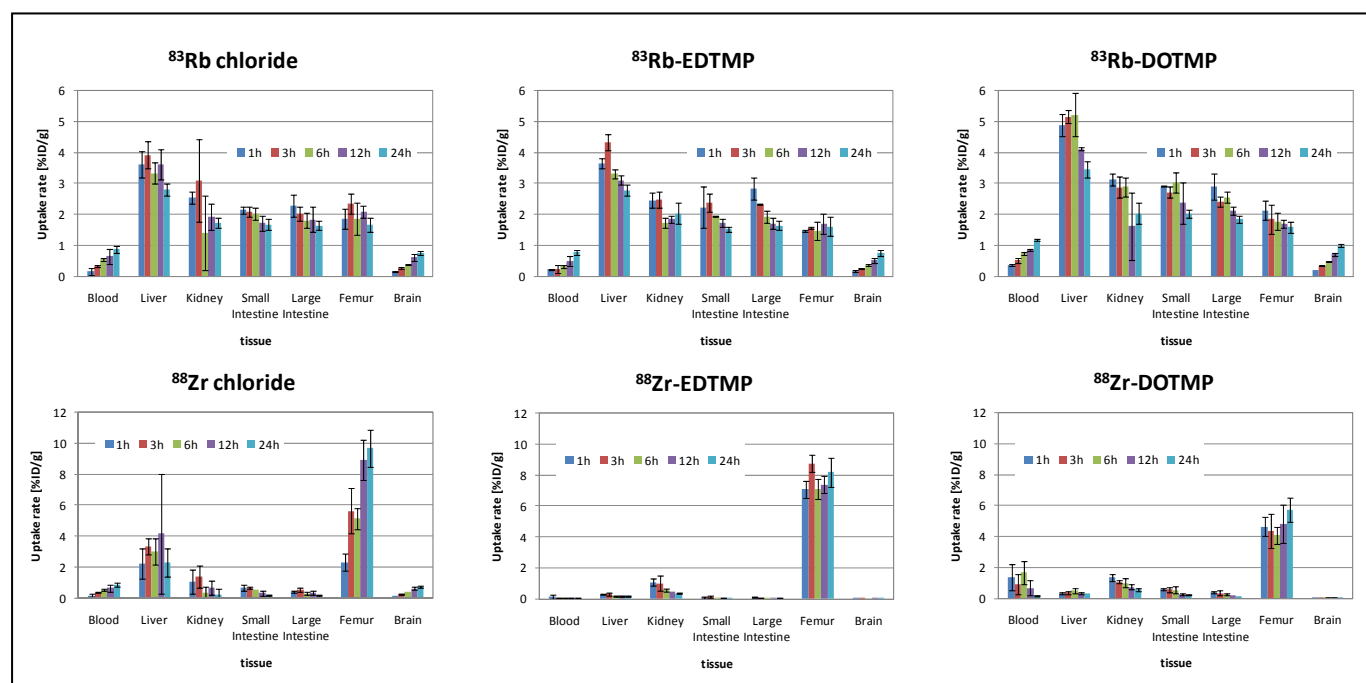
Fig.1 Biodistribution of ^{83}Rb chloride, ^{83}Rb-EDTMP, ^{83}Rb-DOTMP, ^{88}Zr chloride, ^{88}Zr-EDTMP, ^{88}Zr-DOTMP in mice

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Preparation of a rotating ^{248}Cm target for GARIS

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We plan to study chemical properties of superheavy elements (SHEs, atomic numbers $Z \geq 104$) by using a gas-jet transport system coupled to the RIKEN gas-filled recoil ion separator (GARIS) at the RIKEN Linear Accelerator Facility (RILAC).[1,2] The SHE nuclides with long half lives (e.g., $^{261a/b}$Rf: 68/3 s, $^{265a/b}$Sg: 9/16 s) used in chemical experiments are produced by hot fusion reactions using actinide targets such as ^{238}U, ^{248}Cm, and ^{249}Bk. Stable targets are much desired due to the extremely low-production cross-sections of SHEs on the order of nanobarn or picobarn. Actinide targets in an oxide form are stable in high-intensity heavy-ion bombardments for prolonged beam irradiation. Here, we report on a procedure to prepare a large and uniform ^{248}Cm$_2$O$_3$ target using a molecular plating method for irradiation using the rotating target system of GARIS.

Figure 1(a) shows a schematic view of the cell used for electrodeposition. A Ti backing foil of 2 μm thickness placed on a water-cooled Ti block was used as a cathode, while a Rh plate of 0.1 mm thickness on another Ti block was used as an anode. A 10 mm thick Teflon® spacer perforated in the shape of a banana was sandwiched by electrodes sealed using 1 mm thick silicon rubber pieces perforated in the same banana shape. The active target area is 2.04 cm^2.

Prior to preparation of the ^{248}Cm target, the electrodeposition conditions were optimized by preparing ^{nat}Gd targets. Gadolinium including ^{88}Y as a yield tracer was purified by a cation-exchange method in HCl-methanol media. Six microliters of 0.1 M HNO$_3$ containing 700 μg of Gd were mixed with 5.5 mL of 2-propanol, and the electrodeposition cell was filled with the mixture. At an applied voltage of 1000 V, the deposition yields increased with electrodeposition time from 52% at 2 min to 100% at $\geq$ 8 min (Fig. 2a). The deposition yields also increased with increasing applied voltage: from 50% at 200V to ~100% at 800 V during the 10 min electrodeposition (Fig. 2b). The uniform target layer is visually observed, and the average-target thickness was 350±10 μg cm^{-2} for the targets electrodeposited for $\geq$ 8 min. The ^{248}Cm targets were prepared after obtaining results for the ^{nat}Gd targets. The isotopic composition of Cm used in this study was ^{244}Cm: 0.024%, ^{245}Cm: 0.13%, ^{246}Cm: 3.17%, ^{247}Cm: 0.04%, and ^{248}Cm: 96.636%. Twenty microliters of 0.2 M HNO$_3$ containing 610 μg of ^{248}Cm was mixed with 5.5 mL of 2-propanol, and the electrodeposition cell was filled the mixture. Electrodeposition was carried out by applying a voltage of 1000 V with an increasing current density from 9.8 to 11.8 mA cm^{-2} for 10 min. During the electrodeposition, the Ti blocks were continuously water-cooled at 10 ℃. After the electrodeposition, the target was dried by an infrared lamp. The ^{248}Cm target

thickness of 320±20 μg cm^{-2} averaged for the 6 targets was determined by γ-ray spectrometry on ^{245}Cm, while referring to the isotopic composition of Cm. The average deposition yield was 100$^{+0}_{-3}$%. Figure 1(b) shows an illustration of the ^{248}Cm target fixed to the target holder. The α activities of the 7 points shown in Fig. 7(b) were measured to confirm the uniformity of the target. The α-particles from the Cm isotopes were collimated with an aluminum slit of 1 mm diameter, and were detected with a Si detector. Standard deviations of the target thickness at the seven points were evaluated to be 11%.

The 6 ^{248}Cm targets were arranged on a rotating wheel of 10 cm diameter, and were irradiated by a 126-MeV ^{23}Na beam with beam currents up to 1 particle μA (50%duty) to produce ^{266}Bh *via* the ^{248}Cm(^{23}Na, 5n)^{266}Bh reaction. [3]
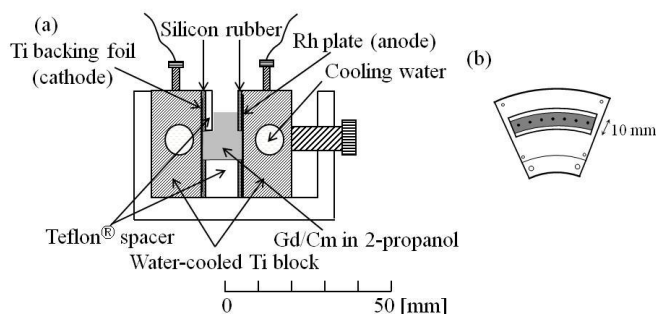
Fig.1. (a) Schematic view of the cell for electrodeposition. (b) Illustration of the Cm target fixed to the target holder. Uniformity of the target was estimated by α-particle measurements at the seven points shown in the figure.
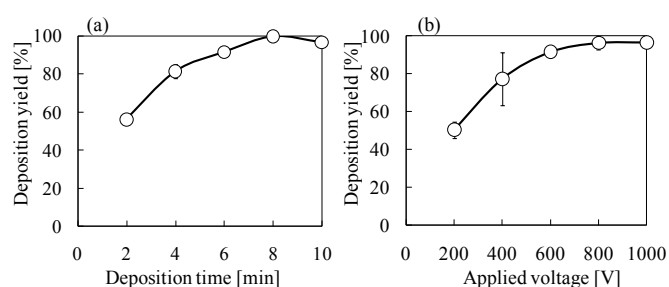
Fig. 2. Dependence of deposition yields of the ^{nat}Gd target on (a) deposition time at an applied voltage of 1000V and (b) applied voltage at an electrodeposition time of 10 min.

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Production of ²⁶¹Rf for chemical studies using the gas-jet transport system coupled to GARIS

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and A. Yoneda

We have been developing a gas-jet transport system coupled to the RIKEN gas-filled recoil ion separator GARIS as a novel technique for superheavy element (SHE, $Z{\geq}104$) chemistry.[1,2] The performance of the system has been investigated using ^{206}Fr, ^{245}Fm, and ^{255}No produced in the ^{169}Tm(^{40}Ar,3n), ^{208}Pb(^{40}Ar,3n), and ^{238}U(^{22}Ne,5n) reactions, respectively.[1,2] The results revealed that the GARIS/gas-jet system is a promising tool for next-generation SHE chemistry, i.e., identifying SHE nuclides under low background conditions with high efficiency of the gas-jet transport. Hot fusion reactions based on a ^{248}Cm target should be considered for producing SHE nuclides with long half-lives for chemical experiments. Since the last experiment with ^{255}No, we have developed a new gas jet chamber having a large focal plane window of 100 mm diameter to efficiently collect evaporation residues. A rotating target system for the ^{248}Cm material was also installed. Recently, ^{261}Rf produced in the ^{248}Cm(^{18}O,5n) reaction was successfully extracted to a chemistry laboratory after physical separation by GARIS.

A ^{248}Cm$_2$O$_3$ target of 280 μg cm^{-2} thickness was prepared by electrodeposition onto a 0.90 mg cm^{-2} Ti backing foil.[3] The ^{18}O^{5+} ion beam was extracted from the RIKEN Linear Accelerator, RILAC. Beam energy was 95.5 MeV at the center of the target, and average beam intensity was 4.8 pμA. The reaction products of interest were separated in-flight from the beam and the majority of the nuclear transfer products by GARIS and then guided into the gas-jet chamber of 100 mm i.d. × 20 mm depth through a Mylar window of 0.5 μm thickness, which was supported by a circular-hole grid with 78% transparency. GARIS was filled with He gas at a pressure of 33 Pa. The magnetic rigidity of GARIS was set at 1.73 Tm. In the gas-jet chamber, the reaction products were stopped in He gas, attached to KCl aerosols, and continuously transported through a Teflon capillary (2.0 mm i.d. × ~10 m length) to a rotating wheel system, MANON, for α spectrometry. The He flow rate was 2.0 L min^{-1}, and the inner pressure of the chamber was 49 kPa. In MANON, the aerosols were deposited on 200-position Mylar foils of 0.5 μm thickness placed at the periphery of a stainless steel wheel of 420 mm diameter. After aerosol collection, the wheel was stepped at 30-s intervals to position the foils between seven pairs of Si PIN photodiodes (Hamamatsu S3204-09). To evaluate the number of ^{261}Rf atoms that passed through the Mylar window of GARIS, the gas-jet chamber was replaced with a detector chamber equipped with nine Si PIN photodiodes (Hamamatsu S3584-09, 3×3 square arrangement).

Figure 1 shows the sum of α-particle spectra measured in the seven top detectors of MANON. The 30-s aerosol collection was repeated 697 times. A beam dose of 6.3×10^{17} was accumulated. As shown in Fig. 1, α peaks of ^{261}Rf (65 s, 8.28 MeV)[4] and its daughter ^{257}No (24.5 s, 8.222 and 8.323 MeV)[5] are clearly seen under the extremely low background condition, suggesting that the gas-jet transport of ^{261}Rf was successfully conducted after the physical separation by GARIS. A total of 168 α events were registered in the energy range of interest, including 58 time-correlated α pairs. The 7.687-MeV peak is due to ^{214}Po, a descendant of the natural radioisotope ^{222}Rn in the room. By comparing the spectrum measured with the focal plane Si detector, the gas-jet transport efficiency of ^{261}Rf was evaluated to be 52±12%. On the other hand, the transport efficiency of GARIS was 7.8±1.7% for the focal plane of 100 mm diameter, referring to the cross section of 13 nb.[6] The present results suggest that the GARIS/gas-jet system is a promising approach for exploring new frontiers in SHE chemistry: (i) the background radioactivies of unwanted reaction products are strongly suppressed, (ii) the intense beam is absent in the gas-jet chamber and hence high gas-jet efficiency is achieved, and (iii) the beam-free condition also allows for investigations of new chemical systems.
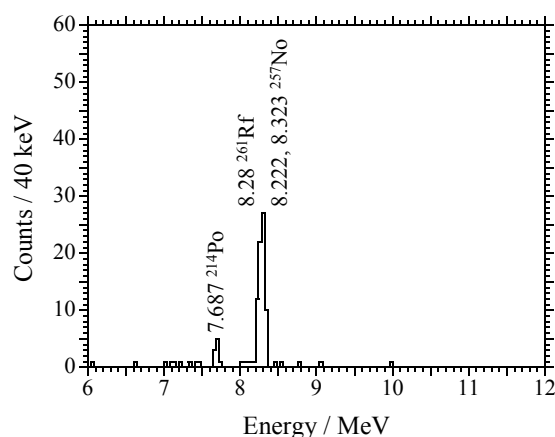
Fig. 1. Sum of α-particle spectra measured in seven top detectors of MANON.

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Production of RI Tracers for chemistry of transactinide elements

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[Radioactive tracer, niobium, tantalum]

Since a transactinide element has a very short life and its production cross-section is very small, only a very little quantity — usually one atom — is handled for a chemistry experiment at a time. To investigate the chemical property of such transactinide element, many repetition experiments in terms of rapid chemistry method are necessary until sufficient statistics are obtained. In other words, it takes very long time to one experimental condition. Thus, the off-line experiment using a light homologue will be valid for an efficient on-line experiment. The aim of this work is to produce the non-carrier tracer for carrying out the off-line chemical experiments.

For the rapid chemistry experiments of Db, the radioactive isotopes ^{95g}Nb ($T_{1/2} = 35$ d) and ^{179}Ta ($T_{1/2} = 665$ d) were selected as a tracer in consideration of whether measuring their gamma-ray (or x-ray) is possible and whether the half life is measurable. The tracers were produced using the ^{96}Zr$(p, 2n)^{95g}$Nb, ^{179}Hf$(p, n)^{179}$Ta and ^{180}Hf$(p, 2n)^{179}$Ta reactions with RIKEN K70 AVF cyclotron. The ^{nat}Zr foil (64.5 mg cm^{-2}) and the Hf foil (141 mg cm^{-2}) covered with aluminum foils were stacked and placed at the irradiation chamber. The Zr target was put on the beam upstream to make the proton energy optimal to the intended nuclear reactions. The proton beam energy was about 14 MeV. The irradiation time was 12 hours, and the average beam current was about 15 μA. The activities of ^{95g}Nb and ^{179}Ta were 4.1 MBq and 3.0 MBq, respectively, after 21 days from the end of bombardment. Those were enough to perform the experiment for a few months.

Each tracer nuclide was separated from the target material using an anion-exchange method. The tracers have been used in different experiments to develop solvent extraction technique for 5th-group elements.

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Extraction of mendelevium (III) and lanthanides (III) from hydrochloric acid solutions to carbon tetrachloride with 2-thenoyltrifluoroacetone

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Chemical properties of trivalent actinides have often been discussed by comparing actinides to lanthanides. The liquid-liquid extraction of trivalent actinides and lanthanides with β-diketonates has been studied thoroughly[1]. However, there are very few reports on the investigation with a series of lanthanides and trivalent actinides in the same extraction conditions. In particular, the data of the elements with atomic number an above 100 are limited because those are produced only in heavy-ion induced nuclear reactions by using an accelerator.

We have performed extraction experiments of americium, curium, californium and fermium with 2-thenoyltrifluoroacetone (HTTA) as an extractant[2]. In this experiment, liquid-liquid extraction of mendelevium (Md) was examined.

Mendelevium-255 was produced in the ^{248}Cm(^{11}B,4n)^{255}Md reaction using the K70 Cyclotron at RIKEN. The produced ^{255}Md was transported to a chemistry laboratory and dissolved in 100 μL of an HCl solution with a pH 2.85 to 3.53 containing 0.1 M NH$_4$Cl. The solution was mixed with an equal volume of 0.1 M HTTA-CCl$_4$ solution. Both phases were shaken for 20 min and centrifuged for 1 min. After phase separation, aliquots of 80 μL of each phase were evaporated to dryness on hot tantalum discs and assayed for alpha activity.

Lanthanide extraction experiments were performed using the RIKEN multitracer. The tracer was stocked in an HCl solution with pH about 3.5. In a test tube, 90 μL of HCl solution with various pH values containing 0.1 M NH$_4$Cl, 10 μL of tracer stock solution and 100 μL of 0.1 M HTTA-CCl$_4$ solution were mixed. The mixture was shaken for 20 min using a vortex mixer and then centrifuged for 3 min. After phase separation, each phase was assayed for gamma activity after which the pH value of the aqueous phase was measured.

The distribution ratio D is obtained by following equation: $D = V_{aq}A_{org} / V_{org}A_{aq}$, where V_{aq} and V_{org} is the volumes, and A_{aq} and A_{org} are the radioactivities of the aqueous and organic phases, respectively.

The log D values of Md as a function of pH value in the aqueous phase are shown in Fig. 1. The gradient decreases with increasing pH value. The slope value changes at pH about 3.1. A similar tendency has been found in lanthanides and other actinides, Am, Cm and Cf. The phenomenon is explained in terms of the formation of a hydroxyl species[3,4]. The reactions of this extraction are explained by Eqs. (1) and (2).

$$M^{3+}_{aq} + 3HTTA_{org} \leftrightarrow M(TTA)_{3\ org} + 3H^+_{aq} \qquad (1)$$
$$MOH^{2+}_{aq} + 2HTTA_{org} \leftrightarrow MOH(TTA)_{2\ org} + 2H^+_{aq} \quad (2)$$
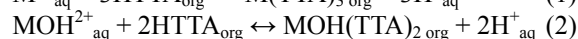
The reaction described by Eq. (1) dominates at lower pH (pH < 3.1). As the pH becomes higher (pH > 3.1), the hydrolysis reaction of lanthanides and actinides occurs, that is, the reaction in Eq. (2) dominates. The log D is described in Eq. (3). When the extraction behavior follows to the Eq. (1), the slope value derived from the linear correlation of log D against pH value should be 3 according to the Eq. (3).

$$\log D = \log K_{ex} + 3pH + 3\log[HTTA]_{org} \qquad (3)$$

As shown in Fig. 1, the linear correlation is found in the lower pH range (pH < 3.1), thus, the equilibrium constant K_{ex} can be estimated, according to Eq. (3). However additional experiments under more various pH conditions are required for deriving a reliable K_{ex} values. The obtained K_{ex} allows us to discuss the reactivity of Md to HTTA.
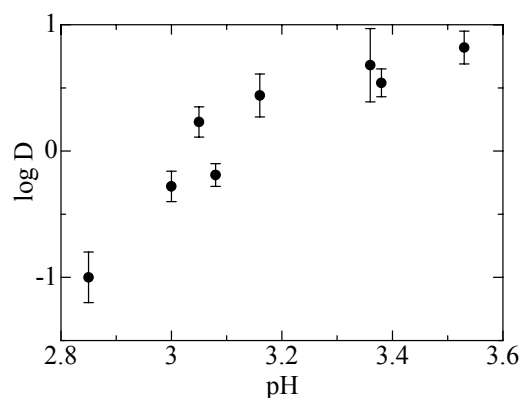
Fig. 1. The extraction behavior of mendelevium from hydrochloric acid solutions to carbon tetrachloride with 2-thenoyltrifluoroacetone

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Studies on solvent extraction behavior of molybdenum and tungsten for solution chemistry of seaborgium (element 106)

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Schädel et al. reported chromatographic behavior of seaborgium (element 106, Sg) in an aqueous solution.[1,2] It was shown that the Sg ion elutes from a cation exchange column in 0.1 M HNO_3/5 × 10^{-4} M HF in the similar behavior as its lighter homologues, molybdenum (Mo) and tungsten (W)[1] and Sg is adsorbed on the cation exchange column in 0.1 M HNO_3 in contrast to Mo and W.[2] However, the chemical experiments of Sg have been limited to the chromatographic method. We have a plan to make a solvent extraction experiment for the chemical study of Sg. In this work, solvent extraction behavior of Mo and W was investigated as a comparative study of Sg. It is generally known that macro amounts of Mo and W form polyoxometalate in the aqueous solution below pH 8–9. However, it is required for the study of Sg to investigate the chemical behavior of mononuclear Mo and W because the production rate of Sg is the order of one atom per hour. To study the solvent extraction behavior of mononuclear Mo and W, the carrier-free isotopes produced by heavy-ion-induced nuclear reactions were used.

Molybdenum and tungsten isotopes, ^{90}Mo ($T_{1/2}$ = 5.7 h) and ^{173}W ($T_{1/2}$ = 7.6 min) were produced in the ^{nat}Ge(^{22}Ne,xn)^{90}Mo and ^{nat}Gd(^{22}Ne,xn)^{173}W reactions, respectively, using the RIKEN K70 AVF Cyclotron. Reaction products recoiling out of the target were stopped in a helium gas flow, attached to KCl aerosols generated by sublimation of KCl powder, and then transported to a chemistry laboratory. The aerosols with reaction products were collected on a polyester or Naflon sheet and were dissolved in 200 μL of 0.1–11 M hydrochloric acid. The concentrations of Mo and W tracers in the aqueous phase were about 10^{-13} M. Equal volume of the 0.05 M tetraphenylarsonium chloride (TPAC)-chloroform or the 0.05 M Aliquat 336-chloroform solution was mixed with the aqueous phase. The mixture was shaken for 15 min in extractions of Mo with TPAC or 3 min in the other experiments. After centrifuging, the aliquots of the aqueous and organic phases were taken, and were subjected to γ-ray spectrometry using Ge detectors. Distribution ratios (D) were obtained from radioactivities of each phase.

Figure 1 shows the distribution ratios of Mo and W as a function of hydrochloric acid concentration [HCl]. The both distribution ratios of Mo and W rise with the increase of [HCl], indicating that the chloride coordinated Mo and W complexes are formed. It has been reported that the extracted species of Mo and W are $MoO_2Cl_3^-$ or $MoO_2Cl_4^{2-}$ and $WO_2Cl_3^-$, $WO_2Cl_4^{2-}$ or $WOCl_5^-$ respectively.[3-5] The distribution ratio of Mo was also investigated in 11 M HCl

as a function of Aliquat 336 concentration to determine the chemical species of Mo. The results are shown in Fig. 2. The plots of log D vs. log Aliquat 336 concentration give a linear correlation with a slope of 1.08 ± 0.04. This indicates that the net charge of Mo chloride complex is -1. Therefore, the extracted species of Mo would be $MoO_2Cl_3^-$. In the near future, the speciation analysis of the extracted W species will be performed. The present results will be also utilized for determination of the experimental conditions for the future chemical studies of Sg.
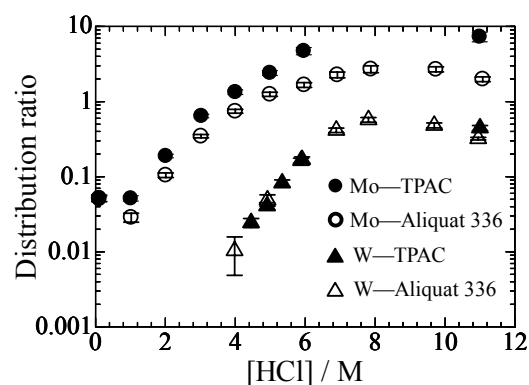
Fig. 1. Extractions of Mo and W from hydrochloric acid with 0.05 M TPAC-chloroform and 0.05 M Aliquat 336-chloroform solution.
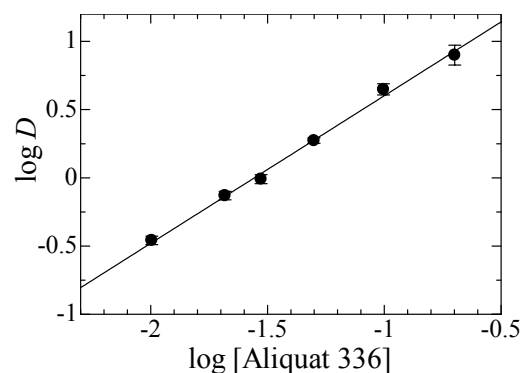
Fig. 2. The distribution ratio of Mo in 11 M hydrochloric acid as a function of Aliquat 336 concentration.

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Adsorption of Nb, Ta and Pa on anion-exchanger in HF/HNO₃ solutions: Model experiments for the chemical study of Db†

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Several model experiments aiming at the chemical study of Db in aqueous solution have been performed using the lighter homologues Nb and Ta, and the pseudo homologue Pa.[1] Although some chemical experiments of Db have been studied,[1] little is known about its chemical properties. For clear understanding of the chemical properties of Db, systematic investigations are strongly required. We plan to investigate the fluoride complexation of Db through anion-exchange experiments in HF/HNO₃; the K_d values of Db will be systematically measured as a function of the ligand (F^-) and the counter-ion (NO_3^-) concentrations as those with Rf.[2] The K_d values of Nb, Ta and Pa on the anion-exchange resin were previously determined as a function of the fluoride ion concentration ($[F^-]$) in HF/HNO₃ at $[NO_3^-] = 0.1$ M.[3] In this work, the K_d values of these elements were measured as a function of $[NO_3^-]$ for further analysis on their fluoride complexation.

The radiotracers ⁹⁵Nb and ¹⁷⁹Ta were produced by the RIKEN K70 AVF cyclotron, and ²³³Pa was separated from ²³⁷Np. The experimental procedures are basically the same as those described in the previous report.[3] The K_d values of Nb, Ta and Pa on the anion-exchange resin in HF/HNO₃ were determined as a function of $[NO_3^-]$ at constant $[F^-] = 2.0 \times 10^{-4}$, 3.0×10^{-3} and 1.0×10^{-2} M.

Variations of the K_d values of Nb, Ta and Pa on the anion-exchange resin in HF/HNO₃ solutions are shown in Fig. 1 as a function of $[NO_3^-]$ at $[F^-]$ of (a) 2.0×10^{-4}, (b) 3.0×10^{-3} and (c) 1.0×10^{-2} M. Distinct difference in the anion-exchange behavior was observed among the elements. The slopes of the fitted linear lines in the $\log K_d$ vs. $\log[NO_3^-]$ plot are presented in Table 1. The net charges of the complexes were evaluated from the slopes for the elements under the following conditions, $[F^-] = 2.0 \times 10^{-4}$ and 3.0×10^{-3} M ((a) and (b)). In the case of (c), the net charge cannot be evaluated due to the effect of HF_2^-. Chemical species were deduced based on the evaluated net charges of the complexes and the knowledge concerning their chemical species in HF solutions as follows; 1) $NbOF_4^-$ would be present at $[F^-] = 2.0 \times 10^{-4}$ and 3.0×10^{-3} M, 2) TaF_6^- is dominantly present at $[F^-] = 3 \times 10^{-3}$ M and Ta seems to be hydrolyzed at $[F^-] = 2.0 \times 10^{-4}$ M, and 3) PaF_6^- and PaF_7^{2-} would be dominantly present at $[F^-] = 2.0 \times 10^{-4}$ and 3.0×10^{-3} M, respectively.

Table 1. Slopes of the fitted linear lines in Fig. 1.

[F⁻] / M	Slope								
	Nb			Ta			Pa		
2.0×10^{-4}	−1.0	±	0.1	−0.5	±	0.1	−1.2	±	0.1
3.0×10^{-3}	−1.3	±	0.1	−1.2	±	0.1	−1.8	±	0.1
1.0×10^{-2}	−1.5	±	0.1	−1.3	±	0.1	−2.0	±	0.1
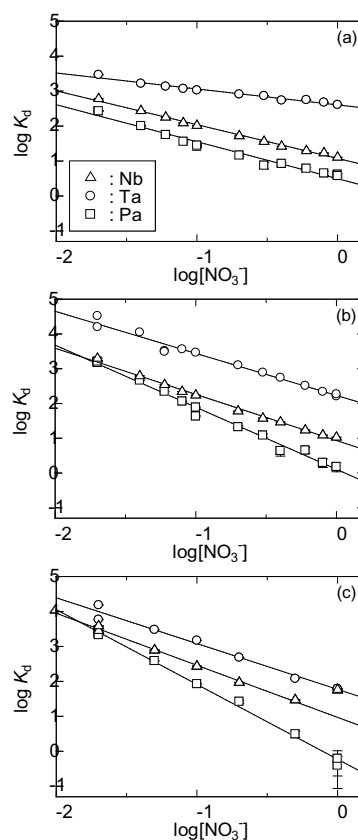
Fig. 1. Variations of the K_d values of ⁹⁵Nb, ¹⁷⁹Ta and ²³³Pa on the anion-exchange resin.

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Development of an electrochemistry apparatus for the heaviest elements†

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It is of great importance to study oxidation states of the heaviest atoms and to determine their oxidation-reduction (redox) potential in aqueous solution. Theoretical calculations predict that oxidation states and redox potentials of the heaviest atoms are influenced by relativistic effects.[1] Thus, electrochemical properties of the heaviest elements will give valuable information on relativistic effects. However, an electric current originating from a redox reaction of one of the heaviest elements is not measureable because of an atom-at-a-time situation. Thus, we developed an electrochemistry apparatus combined with a chromatographic separation technique available even to single atoms. This report describes the development of this electrochemistry apparatus.

Figure 1 shows a schematic diagram of the electrochemistry apparatus, which is based on an electrolytic cell.[2,3] A solution containing the heaviest elements fed from the inlet passes through a working electrode made of glassy carbon fibers packed into a vycol-glass tube and flows out of the outlet. The surface of the fibers is chemically modified with a polyelectrolyte material of Nafion perfluorinated ion-exchange resin,[4,5] so that the working electrode works just like a cation-exchange column. Ions are oxidized on the electrode according to their redox potentials, and the resulting oxidized species are separated from non-oxidized species by cation-exchange chromatography.

Test experiments were performed using the present apparatus for an oxidation reaction of 10^{10} atoms of ^{139}Ce. The radioisotope ^{139}Ce was produced by the ^{139}La(p,n) reaction at the RIKEN K70 AVF cyclotron. The produced ^{139}Ce was chemically separated from the target material by a cation-exchange method and was then stored in 0.1 M α-hydroxyisobutyric acid (α-HIB) solution together with ^{88}Y^{3+}, ^{88}Zr^{4+}, and ^{175}Hf^{4+} which were mixed for comparison of their behavior as typical trivalent and tetravalent ions. We investigated elution behavior of these radiotracers from a chemically-modified electrode with applied potentials of 0.2 - 1.0 V versus an Ag-AgCl reference electrode. With an applied potential of 0.2 V, elution of ^{139}Ce followed that of ^{88}Y. This elution behavior of ^{139}Ce shows that Ce is bound in the most stable trivalent state. At a higher potential of 1.0 V, ^{139}Ce was eluted together with ^{88}Zr and ^{175}Hf. This indicates that ^{139}Ce exists as a tetravalent ion. With intermediate potentials around 0.75 V, elution behavior of ^{139}Ce varied from that of Ce^{3+} to that of Ce^{4+}. An electric potential of 0.75 V is almost equal to that determined by

cyclic voltammetry with 0.001 M Ce in 0.1 M α-HIB. These results show that ^{139}Ce in the trivalent state is successfully oxidized to the tetravalent state using the present apparatus on a tracer scale. Electrochemical oxidation of nobelium will be performed in the near future.
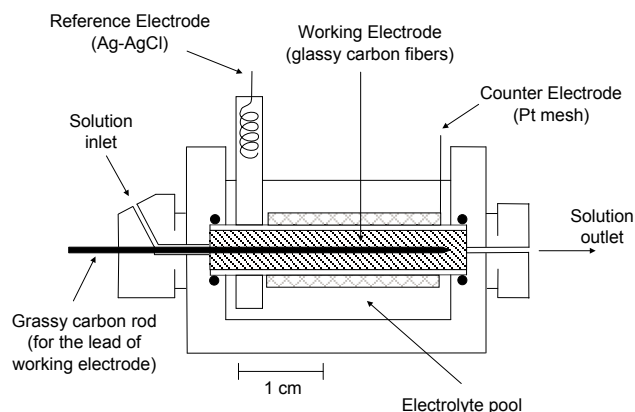
Fig. 1. Schematic diagram of developed electrochemistry apparatus.

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4. Radiation Chemistry and Biology

Ion irradiation in a micro-volume of a cell with a micro beam system for cell irradiation using a tapered glass capillary with end-window

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Research and development of ion irradiation for micro-volume of living cell, has been in progress at RIKEN. Several research groups have been intensively working on the preparation of $\sim$MeV microbeams for biological applications.[1–3] In the conventional scheme, a well-focused energetic ion beam is extracted in air via a vacuum isolation window or micro-size aperture, and then injected into a biological cell in water. One of the drawbacks of these schemes is that a relatively large cylindrical volume is damaged along the beam trajectory in addition to the targeted point. To overcome this technical problem, we have developed a scheme using a tapered glass capillary with a thin window at its outlet.[4] This "cell surgery" scheme can realize pinpoint energy deposition and three-dimensional selection of the bombarded point by observing the outlet through a microscope with micron precision or better at an arbitrary position in a living cell.

The tapered glass capillary is $\sim$50 mm long with inlet and outlet diameters of 0.8 mm and several micrometers, respectively. Figures 1(a) and 1(b) show an optical microscope image and a scanning ion microscope (SIM) image near the capillary outlet, respectively. The end-window is vacuum-tight and the outlet can be safely dipped in liquid. The transmitted beam can be injected into a liquid target at a well-defined position in front of the capillary.[4]

Figure 2 shows the design of a micro beam system for cell irradiation using a capillary installed downstream of the electrostatic tandem accelerator (Pelletron) at RIKEN. To irradiate a living cell in a petri dish, the system consists of three bending magnets, a transport beam line at 45 degrees, and a fluorescent and phase contrast microscope installed on a three-dimensional stage in a darkroom.

Figure 3(a) shows an image of an anchor HeLa cell nucleus labeled with a fusion protein of histone H2B and green fluorescent protein (GFP).[5] An ion beam

Fig. 2. Design of RIKEN micro beam system for cell irradiation. The system consists of three bending magnets, a transport beam line at 45 degrees, and a fluorescent and phase contrast microscope installed on a three-dimensional stage in a darkroom.

of 1 MeV H^+ from PELLETRON was injected into a tapered glass capillary with an end-window of 8 μm in thickness and outlet diameter of 5 μm. Figures 3(b) and 3(c) show the fluorescence images of the nucleus before and after irradiation with transmitted current $\sim$10 pA and $\sim$20 s, respectively. We have demonstrated that a micro beam system for cell irradiation using a tapered glass capillary with a thin end-window can deposit energy in a micro volume of a cell. A tool enabling "surgery" in an arbitrary region of a living cell is now available, providing a technique for studying various functions of intracellular structures independently.
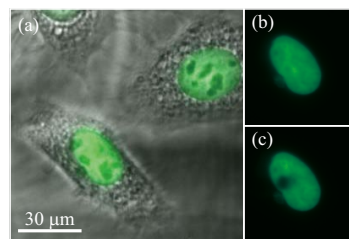
Fig. 3. Images of anchor HeLa cells nucleus labeled with histone H2B-GFP.[5] (b) and (c) are the fluorescence images before and after irradiation, respectively.

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Fig. 1. (a) and (b) are a microgram of the capillary outlet and a diagonal image of the capillary outlet by SIM, respectvely.[4]

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γ-H2AX Foci Formation After Argon Beam Irradiation to the Cultured Animal Cell

K.Takagi[*1], T. Tsukada, M. Izumi, Y. Kazama, Y. Hayashi, and T. Abe

Histone 2AX(H2AX) is a member of histones, which composes a part of a core-histone of the chromatin. When DNA double strand break (DSB) is provoked, Ser139 residues of H2AXs surrounding the breaking point are phosphorylated to form phosphorylated H2AX (γ-H2AX) focus[1]. Therefore, it is possible to assume γ-H2AX foci as landmarks of DSB.

To investigate the distribution of DSBs after the heavy ion-beam irradiation, Ar-beams ($^{40}Ar^{+17}$, 95 MeV/u) were irradiated to mouse fibroblast cell line BALB-3T3 cultured in the confluent condition. Beams of various LET values were irradiated to the cells at the same fluence (15 ions/100 μm^2). Thirty minutes after the irradiation, cells were fixed and localization of γ-H2AX was detected by the indirect immunofluorescence method. The fluorescence of cells was observed by laser-confocal microscopy.
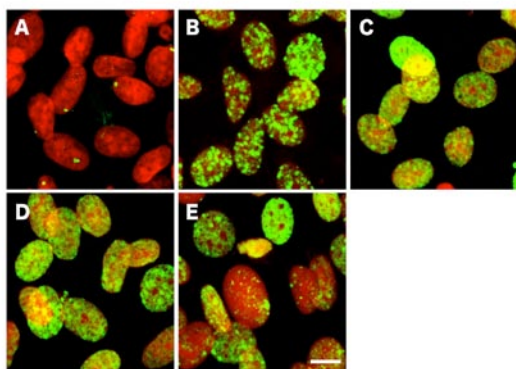
Fig. 1. Localization of γ-H2AX immunofluorescence in Ar-beams irradiated cells.
Red color depicts localization of nuclei, and yellow color indicates γ-H2AX localization. A: control, B: 313 keV/μm, C: 656 keV/μm, D: 1130 keV/μm, E: 1940 keV/μm. Bar = 10 μm.

Figure 1 depicts the γ-H2AX immunofluorescence after the irradiation of Ar-beams of various LETs. In 313 keV/μm Ar-beam irradiated cells, large γ-H2AX foci were observed in the nuclei. The outline of the focus was obfuscated by diffused fluorescence. In 656 keV/μm and 1130 keV/μm beams, γ-H2AX fluorescence seemed to expand whole nuclear area. It was hard to distinguish clear foci structure in nuclei. Strange result was observed in 1940 keV/μm Ar-beam irradiated cells. Some cells revealed very large foci in the nuclei, others revealed pan-nuclear fluorescence, and revealed weak fluorescent signal.
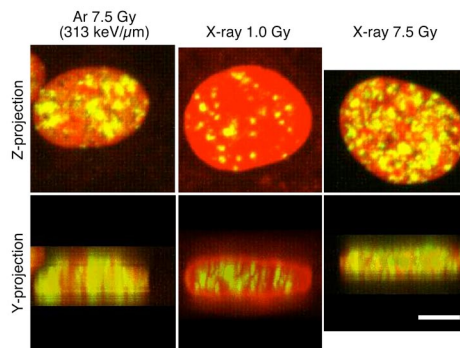
Fig. 2. Comparison of γ-H2AX foci between Ar- and X-ray irradiation. Bar = 5 μm.

In 313 keV/μm Ar-beam irradiated cells, mean number of foci per 100 μm^2 nuclear area was 19.4 ± 5.6 (n=30). The value was close to the fluence of the beams. In 1.0 Gy X-ray irradiated cells, mean number of foci was 14.8 ± 8.6 (n=20). The mean volume of a focus was about 11 fold greater in Ar-irradiated cells than in X-ray irradiated cells (1.91 μm^3 in Ar-irradiated cells vs. 0.17 μm^3 in X-ray irradiated cells). Figure 2 depicts a nucleus of 7.5 Gy Ar-beam (313 keV/μm), 1.0 Gy X-ray (150 kV), and 7.5 Gy X-ray irradiated cell, respectively. In Ar-irradiated cell, many foci penetrated from top to bottom of the nucleus. On the other hand, they rarely penetrated the nucleus in the case of X-ray irradiation. At the same dose (7.5 Gy), X-ray-evoked foci were distributed within the whole nuclear area. These results suggest that high-LET Ar-beams cause multiple DSBs in the restricted nuclear volume along the beam track.

In the present report, we examined the effect of Ar-beam irradiation on localization of γ-H2AX in different LETs. We found that clear γ -H2AX foci were formed at LET value of 313 keV/μm. The number of the foci was close to the fluence of the beam. Many foci penetrated the nucleus and mean focus volume was much greater than in the case of X-ray irradiation, suggesting multiple DSBs along the beam track. At higher LET (656 and 1130 keV/μm), γ -H2AX diffusely expanded in whole nuclear area, rather than formed clear focal structure. This was probably due to the expansion of affecting volume by one particle with increasing LET and/or the increase of actual fluence caused by the Ar-ion disruption. The localization of γ -H2AX was quite different from cell to cell at 1940 keV/μm. That might be due to the heterogeneous distribution of particles at this LET (very close to the Bragg's peak in this experiment).

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Trichostatin A facilitates the phosphorylation of histone H2AX after X-ray irradiation in normal human fibroblast

M. Izumi

In eukaryotes, DNA is packaged into nucleosomes, which are in turn arranged in various higher order structures to form chromatin.   The chromatin structures are regulated by histone modifications and chromatin-associated factors, and thereby contribute to the formation of domains within the genome, referred to as euchromatin and heterochromatin. The chromatin structures are involved in many aspects of DNA metabolism including DNA replication, recombination, and transcription.   However, it is unknown how repair reactions and checkpoint responses after exposure to ionizing radiation are regulated by the chromatin structures.

Histone H2AX is a histone variant and is rapidly phosphorylated following double-strand breaks induced by ionizing radiation.[1]   Histone H2AX is phosphorylated in large chromatin domains flanking DNA double-strand breaks and seems to recruit DNA damage repair proteins including Mre11/Rad50/Nbs1 complex, Brca1, NFBD1, 53BP1, cohesin complex and several chromatin remodeling factors.

I have been focusing on the relationship between chromatin structure and DNA damage response.   My previous experiments showed that DNA double strand breaks induced reduction in the rate of DNA synthesis more efficiently in the heterochromatic region than in the euchromatic region.[2]   We also found that the foci of phosphorylated histone H2AX were not detected in the pericentric heterochromatin in the presence of DNA replication inhibitors, which induce phosphorylation of histone H2AX adjacent to DNA replication fork by ATR.[3] These results suggest that the efficiency and the mechanism of DNA repair are affected by the chromatin structures.

To examine the roles of chromatin structure in DNA repair, we examined the damage response after cells were treated with trichostatin A (TSA), which is an inhibitor of histone deacetylase and alters the chromatin structures in this study.   Human normal fibroblast NB1-RGB cells (population doubling level = 21) were irradiated with 10 Gy of X-ray after the pretreatment of 5 µM TSA.   Then the cell extracts were prepared in the presence of phosphatase inhibitors, and phosphorylated histone H2AX was detected by immunoblotting (Fig. 1).   The phosphorylated hisotone H2AX rapidly increased after irradiation and decreased gradually.   Pretreatment of TSA increased the phosphorylated histone H2AX by 2.5-fold 1 h after irradiation, and a substantial amount of the phosphorylated form remained 5 h after irradiation.   This result suggests that "loosened" chromatin structure makes damage recognition easier and facilitates the damage response.

Now we are investigating whether TSA has the same effect on the damage response after heavy-ion irradiation. We are also trying to directly quantify the amount of DNA damage and cell survival after the pretreatment of TSA.
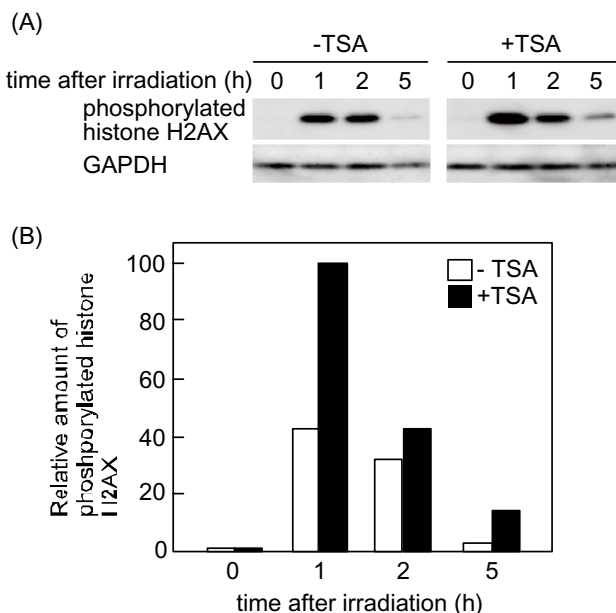
Fig. 1 Western blot analysis of phosphorylated histone H2AX after X-ray irradiation.   A, human NB1-RGB cells provided by RIKEN cell bank were irradiated with 10 Gy of X-ray using Softex (Rigaku).   Whole cell extracts were then prepared at indicated time points and subjected to immunoblotting.   As a loading control, glyceloadehyde-3-phospho dehydrogenase (GAPDH) was detected.   B, the intensity of each band was measured using luminoimage analyzer LAS3000 (Fuji Film) and normalized against the amount of GAPDH.

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Cell-killing effect of low dose of high-LET heavy ions (II)

M. Tomita,[*1] T. Tsukada, and M. Izumi

Radiation-induced bystander responses are defined as responses in cells that have not been directly targeted by radiation but are in the neighborhood of cells that have been directly exposed.[1] In a space environment, astronauts are exposed to low fluencies of high-LET radiation. In addition, normal cells surrounding a tumor also undergo exposure in heavy-ion cancer therapy. Therefore, bystander responses induced by a low dose of high-LET radiation are an important problem in radiation biology. In our study we aim to clarify the molecular mechanisms and biological implications of bystander responses induced by low doses of high-LET radiation. Previously, we reported that the cell-killing effect of high-LET iron (Fe) ions is significantly higher than that of low-LET X-rays under 0.2 Gy.[2] Here we show the progress of results reflecting new data.

Figure 1 shows the clonogenic surviving fraction of normal human lung embryonic fibroblast WI-38 cells irradiated with 250 kV X-rays (2 keV/μm) or 90 MeV/u Fe ions at 1000 keV/μm. WI-38 cells were plated on a 25 cm^2 cell culture flask for one week before irradiation to form confluent monolayers. The surviving fraction was determined by a colony formation assay. The radiosensitivity of WI-38 cells to Fe ions was higher than that to X-rays (Fig. 1A). Surviving fractions (SFs) at doses (D) above 0.1 Gy were fitted by the linear-quadratic model (L-Q model). Cell survival curves for cells irradiated with X-rays and Fe ions were

$$SF = exp(-0.045D^2 - 0.40D)$$

and

$$SF = exp(0.036D^2 - 0.81D)$$

respectively. The doses resulting in 10% cell survival (D_{10}), calculated from the cell survival curves, were 4.02 Gy and 3.32 Gy for X-rays and Fe ions, respectively. The RBE relative to X-rays was 1.21. Figure 1B indicates the surviving fractions at doses of less than 0.5 Gy. At lower doses, the surviving fractions for Fe ions were much lower than those extrapolated from higher doses above 0.1 Gy using the L-Q model. These results suggest that high-LET Fe ions show low-dose hypersensitivity. In addition, the surviving fractions for Fe ions were much lower than those for X-rays. The values of D_{95} were 0.12 and 0.018 for X-rays and Fe ions, respectively. The RBE was 6.8 suggests that a low dose of high-LET radiation can induce cell death more efficiently than low-LET radiation.

The average size of the nucleus of WI-38 was 188 μm^2. The average number of ion tracks per nucleus was calculated as 0.11 in the nuclei of cells irradiated with 0.1 Gy of Fe ions. Thus, nonirradiated cells exist in the same population. Our present results suggest that a low dose of high-LET Fe ions shows low-dose hypersensitivity induced by bystander response.
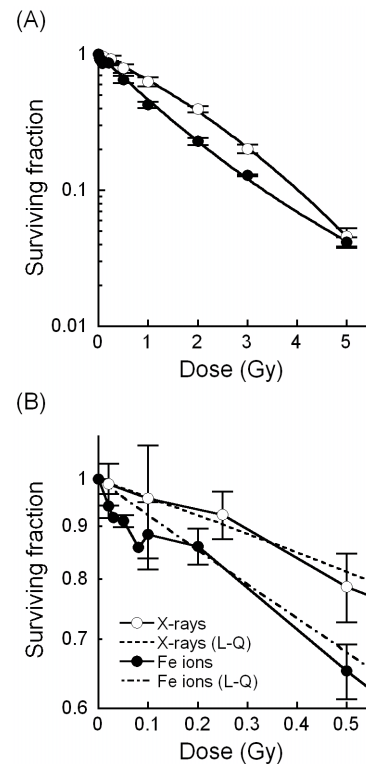
Fig. 1. Cell survival curves of normal human fibroblast WI-38 cells. Confluent monolayers of normal human fibroblast WI-38 cells were irradiated with 250 kV X-rays (2 keV/μm) and 90 MeV/u Fe ions (1000 keV/μm). Cells were harvested and plated 24 h after irradiation. Surviving fractions (SFs) were normalized to those for nonirradiated controls. A shows all SFs obtained in this study and cell survival curves calculated by the linear-quadratic (L-Q) model using SFs at doses above 0.1 Gy. B shows SFs at doses under 0.1 Gy. Error bars of the SFs represent the standard errors of the means (SEMs).

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Carbon-ion induced mutation frequencies and spectra in double strand break repair-deficient mutants of *Neurospora crassa*

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Our lab is interested in how homologous recombination (HR), non-homologous end-joining (NHEJ) and the MRX (Mre11-Rad50-Xrs2) complex coordinate to repair DNA damage arising from carbon-ion irradiation. To this end, we used the filamentous fungus *Neurospora crassa* to examine the killing and mutagenic effect of a carbon-ion beam on a wild type and three DSB repair-deficient mutant strains, *mus-52* (*YKU80*), *mei-3* (*RAD51*) and *uvs-6* (*RAD50*), which are deficient for NHEJ, HR and the MRX complex, respectively.

For each of the *N. crassa* strains examined, 8 ml of conidia (4×10^6 conidia/ml) were transferred to a 15 ml centrifuge tube that was subsequently irradiated with carbon-ions ($^{12}C^{5+}$; 135 MeV/u) at doses of 25 to 400 Gy. Following irradiation, samples were plated on Fries' medium supplemented with 2% sorbose. For the wild type, *mus-52* and *mei-3* strains, each plate was inoculated with 2×10^3 conidia, while for the *uvs-6* mutant, the inoculum size was doubled. After two days at 30°C, the survival rate for each dose of the carbon-ion beam was calculated using unirradiated plates as a control (Fig.1). Among the strains and doses tested, the *uvs-6* mutant always showed the highest sensitivity to the carbon-ion beam, suggesting that the MRX complex has an important role in protecting the cell from carbon-ion induced damage. Sensitivity of the *mus-52* mutant was higher than that of the wild type and *mei-3* strains for carbon-ion doses below 50 Gy. However, the *mus-52* mutant was less sensitive to the carbon-ion beam than the *mei-3* mutant and the wild type strain at doses over 100 Gy and 150 Gy, respectively. From these results, we speculate that DNA damage induced by higher doses of the ion beam (>100 Gy) are repaired mainly by HR, while damage sustained from lower doses (<50 Gy) are fixed through NHEJ.

The frequency of induced mutation was determined by measuring the rate of forward mutation occurring at the *ad-3A* (*adenine-3*) or *ad-3B* locus. Mutations at either of these loci can interfere with adenine biosynthesis, causing the accumulation of a metabolic intermediate that results in purple colonies. For each strain examined, 5×10^5 irradiated but viable conidia were used to inoculate a 5 L Florence flask, which was cultured in the dark at 30°C with low aeration. After 1 week of growth under such conditions, each germinating conidium formed a bead-like colony in the liquid medium. The number of purple colonies that formed in each flask was used to calculate the frequency of mutation at the *ad-3* loci (Fig.2). At a dose of 100 Gy, the mutation frequency of the *mus-52* strain was ~2.8-fold lower than that of the wild type strain. Conversely, the *mei-3* strain had a ~3.0-fold higher frequency of mutation than wild type. These results suggest that an error free repair pathway (i.e. HR) predominantly functions in the *mus-52* strain, while mutations occurring in the *mei-3* strain are mainly repaired through an error prone and/or mutagenic pathway (i.e. NHEJ).

The purple colonies obtained above were characterized as *ad-3A* or *ad-3B* mutants through complementation tests using forced heterokaryons. To determine the type of mutation induced at each locus, genomic DNA was purified from each strain and the sequence of the *ad-3A* (924 bp) or *ad-3B* (2501 bp) gene was analyzed. Results obtained from three independent irradiation experiments are summarized in Figure 3. In the wild type strain, the most common mutation induced by the carbon-ion beam was a deletion of the 715th nucleotide of the *ad-3A* gene (Fig.3). On the other hand, carbon-ion irradiation of the *mei-3* strain frequently induced transitions between the 100th and 300th nucleotide of this gene. Exposure of *mus-52* to carbon-ions generated mutations within *ad-3B*, but not *ad-3A*. A complete comparison of the *ad-3B* mutation spectra from wild type and each of the DSB repair-deficient strains will soon be reported.

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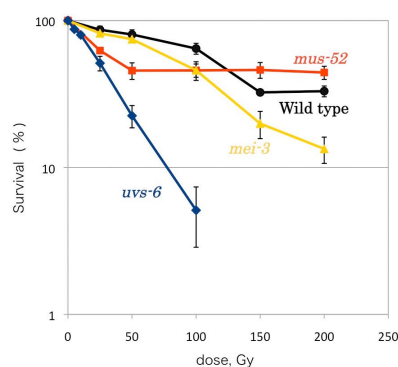
Fig. 1 Percent survival of strains irradiated with a carbon-ion beam
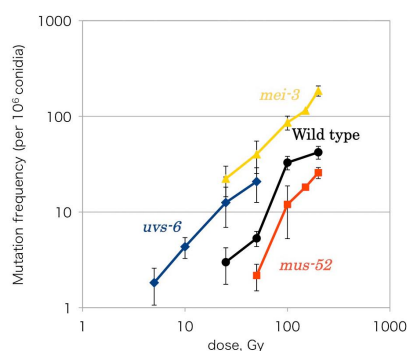
Fig. 2 Mutation frequency of the *ad-3* locus in carbon-ion irradiated strains
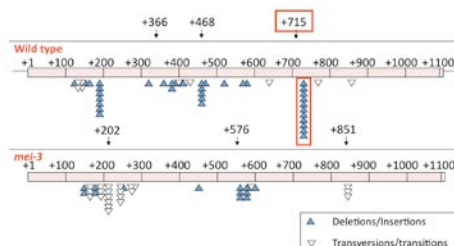
Fig.3 Mutation spectrum of *ad-3A* in wild type and *mei-3* strains

Efficient visualization of microbial mutations using DNA two-dimensional electrophoresis display

H. Ichida, T. Matsuyama, T. Koba,[*1] and T. Abe

Recent advances in DNA sequencing technology have enabled the sequencing of entire genomes of several species of plants and microbes and the resulting data has allowed a comprehensive identification of microbial mutations induced naturally or artificially. To examine genome profiles, we used the method of restriction landmark genome scanning (RLGS), which is a two-dimensional DNA electrophoresis method in which restriction enzyme recognition sites are labeled with radioisotopes as landmarks and are visualized as spots on X-ray films.

This method has several major advantages compared with other DNA analysis methods: 1) almost 3,000 spots can be clearly visualized on film; 2) RLGS spots linearly reflect the copy numbers because there are no amplification steps and no bias in the detection step; 3) the recent development of an computer simulation-based analysis called *in silico* RLGS enables a comparison between two RLGS images, one obtained experimentally (real image) and the other by computer simulations based on whole genome sequences (*in silico* image); and 4) the cost per spot is several times lower than other techniques such as microarray and next-generation sequencing.

We obtained RLGS images of *Mesorhizobium loti* MAFF303099 with several enzyme combinations. The most important step in RLGS analysis is selecting landmark enzymes that produce well-focused and informative spot patterns. We used *Asc*I, *Bsp*EI, and *Not*I as landmark enzymes and observed approximately 1071, 979, and 1025 spots respectively. When real and *in silico* images of *M. loti* MAFF303099 were compared, most of the spots matched the simulated images and we obtained profiles with almost complete linkage between RLGS spots and sequences (Fig. 1).

The ability of *in silico* RLGS analysis to comprehensively predict genome changes was examined. We found that the spots located between 500 and 15,000 bp in the first dimension and between 100 and 1000 bp in the second dimension always showed sufficient resolution and reproducibility with every enzyme combination used. The first-dimension coverage of *M. loti* MAFF303099 with the enzyme combinations of *Asc*I–*Mbo*I, *Bsp*EI–*Mbo*I, and *Not*I–*Mbo*I was 42.3, 61.8, and 49.2% respectively. Overall, the first dimension coverage of the three enzyme combinations without duplication was 87.3%. This result clearly demonstrates that RLGS analysis combined with *in silico* profiling enables efficient and high-density scanning for mutations over the entire genome with good resolution.
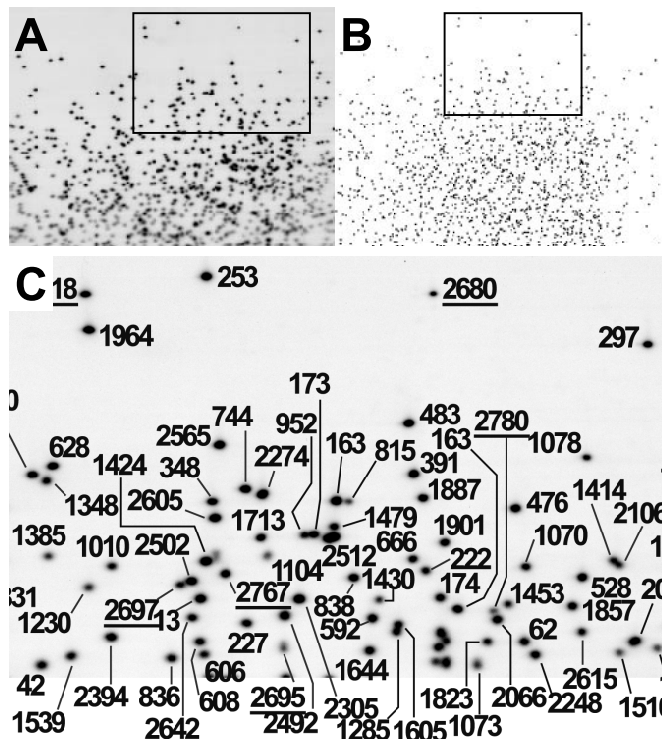
Fig. 1. Comparison between real and *in silico* RLGS images of *M. loti* MAFF303099. (A) Real RLGS image with *Not*I and *Mbo*I. (B) *In silico* RLGS image calculated based on the whole-genome sequence. (C) Boxed regions in A and B were compared and corresponding pairs of spots were shown on the real RLGS image with numbers (Non-underlined: chromosome, underlined: pMLa).

Computer simulation showed that RLGS analysis with three or four combinations of landmark enzymes covers 80% or more regions of the genomes in *Bradyrhizobium japonicum* USDA110, *Pseudomonas syringae* pv. *tomato* DC3000, *Xanthomonas oryzae* pv. *oryzae* MAFF311018. Therefore, *in silico* RLGS is applicable not only to *M. loti* but also other bacteria whose complete genome sequences are available and is universal technique to identify microbial mutations. We previously showed that accelerated heavy-ions cause insertions and deletions on microbial genomes[1] suggesting that the combination of heavy-ion beam irradiation and *in silico* RLGS enables efficient induction and identification of microbial mutations.

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Characterization of floral homeotic mutant, *Meshibedarake*, induced by C-ion beam irradiation

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Tomoko Abe

Previously, we examined the effects of heavy ion beams on plant-mutation induction in developing embryos, seeds, in vitro cultured cells, in anther culture and leaf cultures of tobacco.[1] Generally, plants are regenerated from anther culture that have haploid genome. Therefore, the mutation induction in anther culture offers the possibilities of screening for recessive mutants in the first generation, selecting for novel genotypes from very large haploid populations, avoiding chimerism and rapidly fixing selected genotypes.

In this study, we identified a novel mutant "*Meshibedarake*" (*md* mutant) that promoted homeotic conversion of stamen into pistil structures in *N. tabacum* (cvs. Xanthi) (wild-type: Fig. A and *md* mutant: B). The *md* mutant was isolated from M_1 plants regenerated by anther cultures that were irradiated with C ions (135MeV/u, LET 23keV/μm) at dose of a 5 Gy. The *md* mutant was sterile, and was determined to be haploid by Flow Cytometer. Therefore, to identify the mutation gene of *md* mutant, we analyzed the detail phenotypes and mutation by using M_1 and clone plants. The *md* mutant showed dwarf-type and had small flower organs as with commonly haploid plant (Fig. C). In addition, the mutant had abnormal organs instead of normal stamens (Fig. D-F). However no obvious morphological changes could be observed in any other part of the flower organs (Fig.A-C). First, to determine the nature of the abnormal organs, we observed the epidermal cell of each flower organ by using scanning electron microscopy (SEM). The all organs except for abnormal organs of *md* mutant were typical of wild-type style. In the abnormal organs, the tip organs (Fig. D, white arrow head) had many trichomes as in the case of the stigma of wild type. Moreover, in the stigmatic organs, wild-type pollen could germinate and the pollen tube could grow as in the stigma of the wild type (Fig. G). The epidermal cell of bottom parts of the abnormal organs (Fig. D, gray arrow head) resembled that of the anthers of the wild type. These results indicate that the abnormal organs of *md* mutant were composed of fused organs between stigma and anther, and the mutant cause conversion of stamens into pistils.

The conversion of the stamen into the pistil in *Petunia* was known as loss of homeotic genes, *GLO*, *DEF* or *TM6*. Therefore, we attempted to identify the mutation gene of the *md* mutant by Southern blot analysis using these candidate genes as probes. The *md* mutant should lack signals that were detected in wild-type, only when the DEF gene was used as a probe (Fig. H). To identify the mutant sequence, we isolated the *DEF* gene

in wild type and the mutant. As a result, we detected deletion of over 4,244bp including *DEF* in the mutant genome. These results suggest that the conversion of the stamens into the pistils of *md* mutant is caused by the loss-of-function in the *DEF* gene. The *DEF* mutant of *Petunia* shows not only the conversion of stamen into pistil, but also the conversion of petal into sepal. The conversion like the *md* mutant had been observed only *N. tabacum*[2]. These results indicate that *N. tabacum* has unique *DEF* function which was different from other Solanaceae plants including *Petunia*.
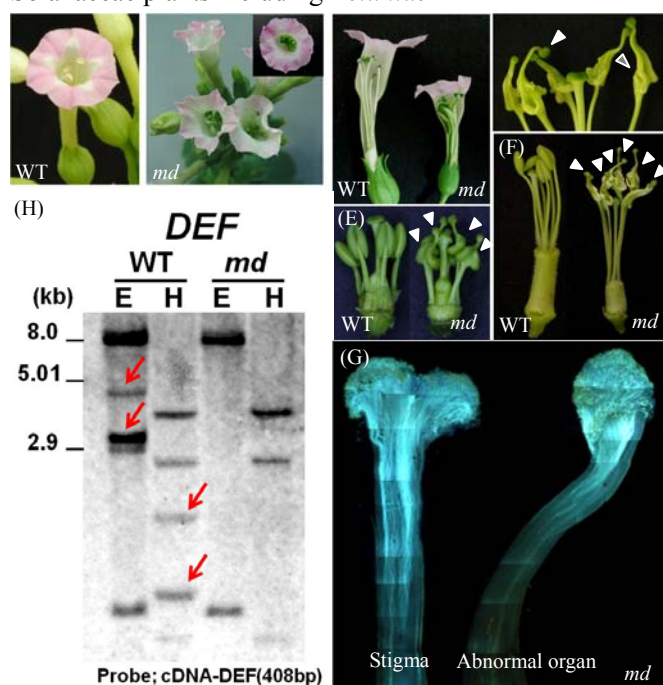
Figure. Phenotype of flower organs of wild-type (WT) and md mutant (A-G), and Southern blot analysis of WT and *md* mutant genomic DNA with a probe for a DEF gene (H). (A) and (B) WT and the *md* mutant flowers, respectively. (C) WT (left) and *md* mutant (right) flower. Petals have been removed partially. (D) Abnormal organs (five organs) and pistil (the center) of *md* mutant. White and gray arrow-heads indicate the tip organ and bottom organ of the abnormal organ, respectively. (E) Buds (sepal and petals have been removed) of WT and *md* mutant at bud-5mm and (F) -20mm stage. These white allow-heads indicate the abnormal organs except for stamens. (G) Pollen tube growths in stigma and the abnormal (stigmatic) organs of *md* mutant. (H) Southern blot analysis of WT and *md* mutant genomic DNAs with a *DEF* probe. Two bands (red arrows) were not detected in *md* mutant genomic DNA after digested with *Eco*RI: E and *Hind*III: H, respectively.

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Identification of deletion mutation induced by C-ion beam irradiation in a tobacco white flower mutant

Yusuke Kazama, Hinako Takehisa, Sumie Ohbu, Hiroyuki Ichida, Yoriko Hayashi and Tomoko Abe

Heavy-ion beam irradiation is widely accepted as a powerful tool for inducing deletion mutations with high efficiency. We are studying the size of deletions induced by heavy-ion beam irradiation in plant genomes, and previously reported a 985-bp and a 440-bp deletion in *Arabidipsis* mutants induced by irradiation with $^{12}C^{6+}$ and $^{14}N^{7+}$ ions, respectively.[1, 2] In this report, we determined a new deletion occurring in a tobacco white flower mutant, x*wf1* (Fig. 1), to obtain more insight into the deletion sizes.

The *xwf1* mutant was induced by $^{12}C^{6+}$-ion beam irradiation (135 MeV/nucleon, 23 keV/μm) at a dose of 20 Gy.[3] Flower colors are most often conferred by the structure of flavonoids. One of the flavonoids, cyanidin is the major component of colored anthocyanidins in the tobacco flower. Cyanidin is produced from dihidrokaempferol by the action of flavonoid 3' hydroxylase (F3'H), dihydroflavonol 4-reductase (DFR) and anthocyanidin synthase (ANS). We previously reported that the *xwf1* mutant did not accumulate cyanidin and pelargonidin but contains dihydrokaempferol and quercetin, which is a product of F3'H action.[3] From the result, it was postulated that DFR or ANS may be defective in the *xwf1* mutant. Thus, we investigated whether the *xwf1* mutant has mutations in the *N. tabacum DFR* gene (*NtDFR*) or the *N. tabacum ANS* gene (*NtANS*).

Southern blot analysis was performed using the DNA fragment coding *DFR* gene as a probe (Fig. 2). Wild-type plant showed four hybridization signals after *Eco*RI or *Hin*dIII digestion, whereas the *xwf1* mutant lacked signals of 8-kb fragment produced by *Eco*RI digestion and of 1.5-kb fragment produced by *Hin*dIII digestion. This result indicates that the *xwf1* mutant would have a deletion mutation in the *NtDFR* gene. When the *NtANS* gene was used as a probe, no signal difference was observed between wild-type and the *xwf1* mutant.

To clarify the deleted region in the *xwf1* mutant, we determined genomic sequences of the *NtDFR* genes in *N. tabacum* cv. Xanthi. Tobacco is a natural allotetraploid derived from the interspecific hybridization of ancestral *N. sylvestris* and *N. tomentosiformis*. Thus, at least two copies per every gene exist in the tobacco genome. Two copies of the *DFR* gene, *NtDFR1* and *NtDFR2*, were previously identified in cv. SN1[4] and in cv. SamsunNN. Two independent genomic fragments, 6,723 bp and 3,847 bp, including *NtDFR* genes were obtained by PCR-based cloning and sequencing (Fig. 3). Sequence homology search using the BLAST program on the GenBank database (http://www.ncbi.nlm.nih.gov/) revealed that the 6,723-bp and 3,847-bp fragments harbors a gene homologous to *NtDFR1* and *NtDFR2*, respectively. The size

of the *Hin*dIII fragment that disappeared in the *xwf1* genome in Southern hybridization analysis (Fig. 2) was corresponding to that of the *Hin*dIII fragment included in the 3,874-bp sequence. This result suggests that the deletion may occur in the *NtDFR2* gene. To ascertain the existence of the deletion in *NtDFR2*, PCR was performed by using *NtDFR2*-specific primers. The fragment containing the *NtDFR2* gene was amplified from the wild-type genomic DNA, but did not from the *xwf1* mutant genomic DNA (data not shown). These results indicate that the *xwf1* mutant has a deletion that is at least larger than 3,874 bp.

Fig. 1. Flowers of the wild-type tobacco cv. Xanthi and the *xwf1* mutant.
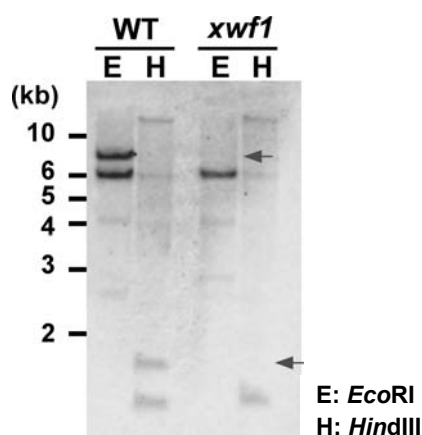
Fig. 2. Southern blot analyses using *NtDFR* gene as a probe. Arrows indicate signals lacking in the *xwf1* mutant.
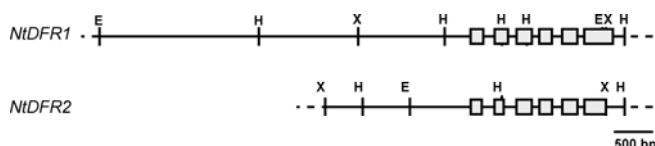
Fig. 3. Genome structures of two copies of *NtDFR* genes.

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Expression analysis of anthocyanin-synthesis related genes in a torenia sector mutant produced by ion beam irradiation

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We have previously reported that the application of heavy-ion beam irradiation to genetically modified torenia (*Torenia fournieri* Lind. 'Crown Violet'; Figure 1A) plants carrying anthocyanin biosynthesis-related transgenes could create various petal color and coloration, and concluded that the combination of ion beam irradiation and genetic engineering efficiently facilitates improvement of agrobiological and commercial traits within a short period

Among the mutants obtained, we chose a sector mutant, 40-53, for our analysis (Figure 1B-a and -b), because we were interested in the unique and novel phenotype in petal coloration, which has never seen before in torenia. The 40-53 mutant was obtained by the ^{20}Ne (25 Gy) ion beam irradiation to CA411-3 (Figure 1A-b) carrying 35S::antisense-chalcone synthase (*CHS*) gene[2]. In this mutant, a large part of the petal showed pale purple (Figure 1B-a, region β), which is slightly fainter than the petals of CA411-3 plants, and a smaller part of petals showed dark purple (Figure 1B-a, region α) as in wild-type torenia (Figure 1A). We assumed that one of anthocyanin biosynthesis-related genes would be deficient in the mutant to be partially restored to dark purple color. To progress in the analysis of the mutant, we cloned 10 torenia anthocyanin biosynthesis-related genes, such as anthocyanin synthase 1 and 2 (*TfANS1* and *TfANS2*), chalcone isomerase (*TfCHI*), chalcone synthase 1 and 2 (*TfCHS1* and *TfCHS2*), dihydroflavonol 4-reductase (*TfDFR*), flavanone hydroxylase (*TfF3H*), flavonoid 3' hydroxylase (*TfF3'H1* and *TfF3'H2*) and flavonoid 3' 5'-hydroxylase (*TfF3'5'H*), and examined the expression of these genes by RT-PCR analysis using petals of α and β regions in the mutant (Figure 1C). The results showed that the expressions of *TfCHS1* and *TfCHS2*, which were not detected in CA411-3 plants, were detected in region α of the mutant. Unexpectedly, the expression of *TfDFR* was up-regulated in CA411-3, and down-regulated in region α of the mutant. Expressions of the other genes were not significantly changed in the mutant.

Because the expression of *TfCHS1* and *TfCHS2* gene were restored in region α of the mutant, we supposed that this phenotype was caused by a mutation, which released the gene silencing of the two genes by the antisense-*CHS*. Alteration of *TfDFR* expression from wild-type torenia would be explained by feedback effect under the control of the expression of *TfCHS* genes, because the *DFR* is downstream of the *CHS* on anthocyanin biosynthesis. Meanwhile, only a single base

mutation would not cause this sector phenotype, and we supposed that an unstable mutation which partially release the gene silencing on a phase of petal pigmentation and coloration, such as insertion of unknown transposable elements[3] and alteration of methylation, would occur around the transgene. We are now trying to isolate and confirm the sequences of transgene including the whole T-DNA region in the mutant. We expect that we would be able to control not only petal color but also petal coloration of torenia plants in the future by elucidation of a gene mutation that causes the phenotype of the 40-53 mutant.

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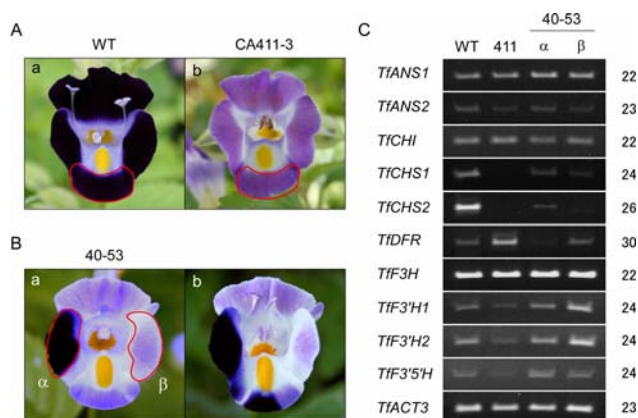
Figure 1. Analysis of 40-53 mutants obtained by heavy-ion beam irradiation. Photographs of WT (A-a), CA411-3 (A-b) and 40-53 mutants (B). (C) RT-PCR analysis of 10 anthocyanin-synthesis related genes, *TfANS1*, *TfASN2*, *TfCHI*, *TfCHS1*, *TfCHS2*, *TfDFR*, *TfF3H*, *TfF3'H1*, *TfF3'H2* and *TfF3'5'H* in petals of WT, CA411-3 and 40-53. In 40-53, dark purple region (α) and pale purple region (β) were used for RT-PCR materials. The torenia actin gene, *TfACT3* (AB330989), was used as an internal control. PCR cycles were indicated on right sides of each column.

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Reduced expression of *flavonoid 3',5'-hydroxyrase* gene in a red-flowered torenia mutant obtained by heavy-ion beam irradiation

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Flower color is one of the most attractive characteristics of ornamental flowers. The color is principally determined by anthocyanins, a colored flavonoid pigment. Enzymes responsible for anthocyanin biosynthetic pathway, including dihydroflavonol-4-reductase (DFR) and flavonoid 3'5'-hydroxylase (F3'5'H), are well established, and the genes encoding them have been used for genetic engineering of flower color modification in petunias, roses, carnations and so on[1]. We have previously generated the transgenic torenia DA416-20 with reduced activity of DFR by overexpressing an antisense gene[2]. DA416-20 plants had light blue petals due to disturbed anthocyanin biosynthesis[3], while the wild type (*Torenia fournieri* Lind. cultivar 'Crown Violet') exhibits violet color (Fig. 1). We have further mutated DA416-20 plants by heavy-ion beam irradiation and have obtained various mutants with flower color variation[4]. Disturbed anthocyanin biosynthesis might account for changed color. To test this hypothesis, we analyzed a mutant line 25-36 which had reddish flowers rather than blueish ones (Fig. 1). Blue color is derived from derphinidin-based anthocyanins, and a key enzyme for derphinidin biosynthesis is F3'5'H. Since cosuppression of the *F3'5'H* gene caused pink colored flowers in *Torenia hybrida*[5], 25-36 plants were expected that the *F3'5'H* gene expression was reduced. Therefore, we first isolated *TfF3'5'H* (*Torenia fournieri F3'5'H*) gene from wild-type torenia. Two cDNA sequences for *TfF3'5'H* were obtained. One encodes 520 aa protein which is comparable to the length of other plant F3'5'H, and another one encodes truncated protein (140 aa) because of frame-shift caused by 1 nucleotide deletion. We refer to them as type A and B, respectively. In addition, three nucleotides were different between two cDNAs. We performed quantitative real time PCR to compare the *TfF3'5'H* expression between wild-type and 25-36 plants. *TfF3'5'H* expression was extremely reduced to 1.3% of the wild type in the line 25-36, while it was not in DA416-20 and other DA416-20-based mutant lines (Fig.2). Sequence analysis revealed that wild-type plants expressed type A *TfF3'5'H*, while 25-36 exclusively accumulated type B *TfF3'5'H*. This result indicate that the reddish flower of 25-36 plants were due to impaired function of TfF3'5'H which is essential enzyme for blue color pigmentation. To investigate whether impaired expression of *TfF3'5'H* was caused by a mutation in this gene, we determined the genomic sequence of *TfF3'5'H* in wild-type and 25-36 plants. However, there was no mutation in the coding region of genomic sequence both of type A and B *TfF3'5'H* in the 25-36 mutant.

We are now trying to elucidate whether there is a mutation in the promoter region of *TfF3'5'H* gene and in the gene which regulates the *TfF3'5'H* expression directly or indirectly. Although it remains to be elucidated what caused reduction of the *TfF3'5'H* expression, we found that heavy-ion beam irradiation has disturbed anthocyanin biosynthesis to alter flower colors.

wild type   DA416-20   25-36

Figure 1. Altered flower color of torenia by molecular engineering.
Mutant line 25-36 was obtained by heavy-ion beam irradiation to DA416-20 plants which was harboring *DFR* antisense gene.
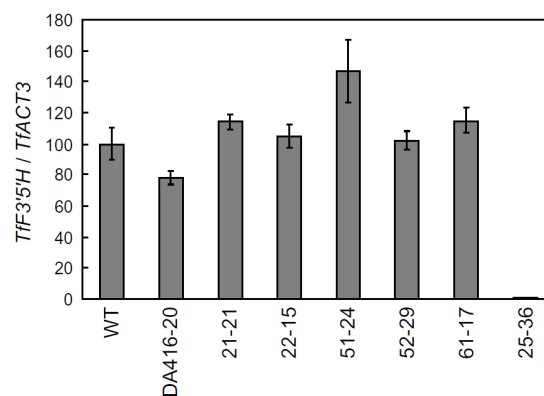
Figure 2. *TfF3'5'H* gene expression.
TfF3'5'H and *TfACT3* expression were analyzed by quantitative real-time RT-PCR. Line 21-21, 22-15, 51-24, 52-29, 61-17 and 25-36 are ion-beam induced mutants of DA416-20 background. Values are average ± SD of three technical duplicates and are represented by relative value to wild type designated as 100.

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Characterization of the GA-synthesis deficient mutants produced by heavy-ion-irradiation

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Mutants in plants are powerful tools for clarifying physiological mechanisms as well as developing new plant varieties in practical breeding programs. Recently, irradiation of plants with accelerated heavy-ion from a ring cyclotron was established as a new effective method to induce mutation. We already reported the effects of heavy-ion bombardment on mutagenesis in sweet pepper (*Capsicum annuum* L., cv. California Wonder) and isolated two dwarf (D, SD) and one xantha mutants from M_1 plants that were irradiated by Ne-ion beams at a dose of 10 Gy. Genetic analysis indicated that these mutants have monogenic recessive mutations in nuclear genes.[1] In this report, we examined two dwarf (D, SD) mutants to clarify their physiological mechanism of dwarfism.

Reciprocal grafting between D or SD and a wild type (WT) indicated that both dwarfisms do not transmit between scion and stock. Some cases of these dwarfisms are caused by defects of gibberellin (GA) biosynthesis or its signal transductions. Thus, we performed a foliar application of GA_3 in the mutants. As a result, shoot elongations were induced in D, SD and WT, especially, that in D is clearer than those in others. We also examined endogenous GAs in their shoot (Fig. 1). As endogenous GAs, GA_1, GA_8, GA_{19}, GA_{20}, and GA_{44} were identified. The levels of GA_{19}, GA_{20}, and GA_{44} in SD were lower than that in WT, whereas in D plant, those of GA_{19}, GA_{20} and GA_8 were lower, but that of GA_{44} were higher than that in WT. These results indicated that D and SD mutant may have a defect in the GA20-oxidase genes.

It is reported that four GA20-oxidase genes may exist in the tomato genome. Based on the sequence information of the tomato GA20-oxidase genes, we designed specific primers and carried out PCR-based cloning of pepper GA20-oxidase genes. Two partial cDNA sequences were obtained. Sequence homology search using the BLAST program on the GenBank database (http://www.ncbi.nlm.nih.gov/) revealed that both sequences are homologous to GA20-oxidase genes. Using one of them (1-kb fragment) as a probe, genomic Southern blot analysis was performed. Wild-type plant and SD mutant showed the same signal patterns after *Eco*RI or *Hin*dIII digestion, whereas D mutant showed different signal size after *Hin*dIII digestion (Fig. 2). This result indicates that a mutation may occur around a GA20-oxidase gene in D mutant. Sequencing analysis of GA20-oxidase gene in D mutant is in progress.

Fig. 1. (A) The GA biosynthesis pathways. Asterisk and box indicate GA20-oxidase-catalyzed reaction and bioactive GAs, respectively. (B) Endogenous GA contents in shoots (4-5 leaf stage). Bars indicate standard error.
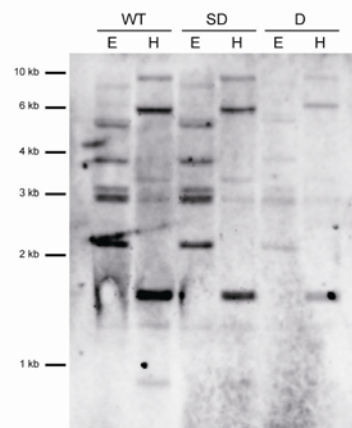
Fig. 2. Genomic Southern blot analysis of GA20-oxicase genes in the pepper dwarf mutants. An asterisk indicates band size shift detected in the D mutant. E: *Eco*RI, H: *Hin*dIII.

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Effect of the heavy-ion beam irradiation on survival rates and sex-reversal mutation in *Silene latifolia*

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The caryophyllaceous perennial herb *Silene latifolia* is a dioecious plant, which has a XY sex determination system. It is presumed that its Y chromosome has three functional regions; the gynoecium-suppressing function (GSF), the stamen-promoting function (SPF), and the anther-maturing function.[1] Though these regions are thought to contain sex-determination genes, those genes have not been identified yet. In the earlier studies on sex-determination of *S. latifolia*, many attempts to get Y-chromosome-deleted mutants were performed; e.g. γ-ray irradiation. Among these irradiated plants, the mutants that lack GSF showed hermaphroditic phenotype and the mutants that lack SPF represented asexual phenotype.[2,3,4] This correspondence relationship supported the existence of sex-determination genes on each functional region. However, no more information was able to be received from these mutants, because most of them are sterile and ephemeral and are now defunct.

Recently, we obtained a novel hermaphroditic mutant by C ion beam irradiation.[5] This mutant is fertile and, interestingly, can produce progenies by self-pollination. Genetic analyses have demonstrated that this mutant has a deletion in Y chromosome. Thus, the ion beam irradiated mutants would be used for isolating sex-determination genes by sequencing deleted regions in the Y chromosome. Mutations of the other regions of Y chromosome will be induced with ion-beam irradiation. Then, we planned to survey the appropriate conditions of irradiation to induce mutations on Y chromosome efficiently.

Dry seeds of *S. latifolia* were irradiated by Fe-ion beams (90 MeV/u, LET 624 keV/μm) at a dose range of 5 to 40 Gy. Wet seeds imbibed for 24h and 28h were irradiated by Fe-ion and C-ion beams (135 MeV/u, LET 23 keV/μm) at a dose range of 2 to 40 Gy and of 5 to 80 Gy, respectively. The effect of each ion beam was observed three weeks after sowing by measuring survival rates (Fig. 1). From the obtained survival curves, the lethal dose 50 (LD_{50}) for dry seed was estimated at approximately 145 Gy of C-ion irradiation and 9 Gy of Fe-ion irradiation. The LD_{50} value for imbibed seeds was estimated to be approximately 30 Gy of C-ion irradiation and 5 Gy of Fe-ion irradiation. As summarized in Fig. 1, the imbibed seeds showed more sensitivity to irradiation than the dry seeds. This difference of sensitivity could be brought about by the difference in the hydration state of DNA and/or free radicals.[6,7] The Fe-ion beam had a stronger effect than the C-ion beam. The

difference in the effect is thought to be because the LET of Fe ions is higher than that of C ions.

Following on from this, we grew the imbibed seeds and screened mutants. We found some mutants including asexual mutants and hermaphroditic mutants among the plants irradiated with C ion at 10 Gy or 20 Gy and the plants irradiated with Fe ion at 4 Gy (Table 1). We deduced that imbibed seed irradiated C ion and Fe ion at 10 Gy and 4 Gy are effective in isolating mutants, respectively. However, we were not able to fix these mutants because they were conspicuously chimerical; for example, there was only one mutated flower in a plant.

These results indicated the possibility of ion beams being able to induce various mutations on Y chromosome. Now, we are screening mutants among Fe-ion-irradiated dry seeds.
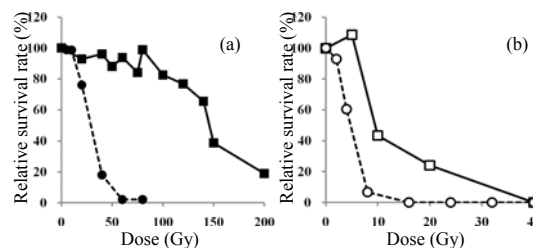
Fig. 1. Survival curve of ion-beam irradiated *S. latifolia*.
(a) Survival curve of C-ion irradiated seeds. (b) Survival curve of Fe-ion irradiated seeds. The longitudinal axis indicates relative survival rate when the control is assumed to be 100. ■, □: survival rate of dry seeds, ●, ○: survival rate of imbibed seeds.

Ion	Dose (Gy)	No. of plants	Number of mutants		
			Asexual	Hermaphrodite	Variegated
C	0	94	0	0	0
	5	89	0	0	0
	10	85	2	1	1
	20	70	1	0	0
	40	16	0	0	0
	60	2	0	0	0
	80	2	0	0	0
Fe	0	101	0	0	0
	2	92	0	0	0
	4	61	0	1	1
	8	7	0	0	0

Table 1. Mutants induced with ion-beam irradiation on imbibed seeds of *S. latifolia*.

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LET-dependent effect of C-ion beam irradiation on mutation induction in Rice.

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Heavy ion beams have high linear energy transfer (LET) and produce more localized ionization than other radiation such as X-rays and γ-rays for the same dose. Therefore, a heavy ion particle is postulated to cause double strand break of DNA and induce mutation with low dose irradiation[1]. LET of ion beams is an important factor affecting mutagenesis. In Arabidopsis, the lethality rate and flowering rate after ion beam treatment are affected by LET. Furthermore, there is an optimum LET value for mutation induction in M_2 plants of Arabidopsis [2]. We examined the effect of LET values on mutation induction in rice.

Imbibed seeds of rice (*Oryza sativa* L. cv. Nipponbare) were exposed to C-ion accelerated to 135MeV/u by RRC. The dose range and the LET range of the C-ion beam were 7.5 to 40Gy and 23 to 60keV/µm respectively. The LET of the C-ion was selected using a range shifter that consists of twelve energy absorbers[3]. The LET values were calculated at the surface of the seeds. After irradiation, seedlings were transplanted into the soil in pots, and grown in a greenhouse. One month after irradiation, plants were transplanted to a paddy field. M_1 plants were harvested approximately 6 months after irradiation. Survival rates and seed fertilities were surveyed in M_1 progenies. M_2 seeds were harvested separately from each M_1 plant. These seeds were sown on seedbeds and grown in a greenhouse for one month to observe mutations. The numbers of CDM (chlorophyll-deficient mutants): albina (albino); xantha (yellow); chlorina (pale green); striata (stripe) were observed.

The survival rate of M_1 plants decreased as the dose increased, and the survival curves differed according to the LET (Fig.1). In over all the fertility of M_2 seeds decreased as the dose increased. There was no significant difference with increased LET values (Fig.2). Mutation rates at 7.5Gy and 10Gy irradiation were low with any

values of LET. In the irradiation at 15 or 20Gy, the higher LET values such as 50 or 60keV/µm were effective in CDM induction (Table.1). These results show that increase of mutation rates could be achieved by controlling LET values in adequate dose irradiation. We are now investigating the effect of higher LET values using Ne ion beams on mutation induction in rice.
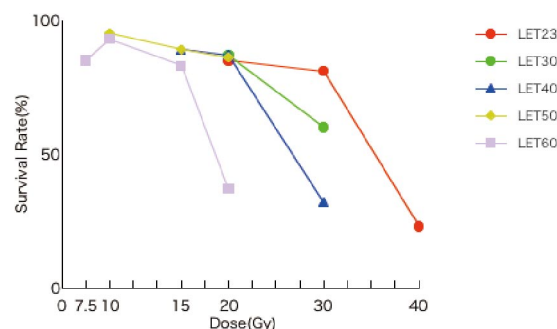
Fig. 1 Survival curves for various LET of C-ion irradiation
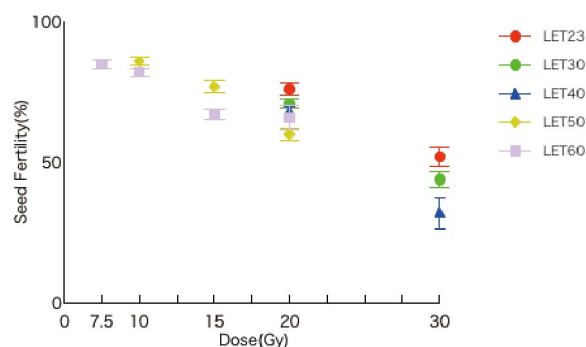
Fig. 2 Relationship between the seed fertility and the dose

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Table.1   Frequency of chlorophyll-deficient mutants (CDM) induced by C-ion beam irradiation

Dose (Gy)	LET (keV/µm)	Survival Rate (%)	Fertile M_1 lines	albina	xanrtha	chlorina	striata	Total CDM	Frequency of CDM (%)
7.5	60	85	127	2	2	0	0	4	3.2
10	50	95	142	2	2	0	0	4	3.3
	60	93	140	2	1	1	0	4	2.8
15	50	89	134	4	5	0	0	9	6.7
	60	83	249	7	2	4	2	15	6.2
20	23	85	127	1	1	1	0	3	2.4
	30	87	261	11	1	1	1	14	5.4
	40	87	260	7	3	2	2	14	5.4
	50	86	258	9	4	1	1	15	5.8
	60	37	56	1	1	2	0	4	7.1
30	23	81	121	2	2	1	1	6	5.0
	30	60	180	6	1	2	0	9	5.0
	40	32	47	1	0	0	0	1	2.1

Harvest from 2005 and 2007.

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Isolation of C-ion induced mutants of strawberry cultivar "Satsumaotome"

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Demand for strawberries in Japan rises at the end of the year. Although the strawberry cultivar 'Satsumaotome' developed by Kagoshima prefecture has large fruits and good eating quality, it is classified as a late-harvesting cultivar, and is not suitable for harvesting at the time with high demand. Recently, heavy-ion beams have been frequently utilized for breeding by artificially inducing mutations in various plant species.[1] Therefore, we examined the possibility of applying heavy-ion beam irradiation to the development of strawberries, and selected earlier-flowering mutants derived from 'Satsumaotome'.

Multiple shoot cultures derived from the shoot apex were used in the irradiation treatments. Cultures were irradiated with C-ion beams whose LETs were controlled to ca. 23 or 48 keV/μm at the surface of the cultures. Shoots developed from their irradiated cultures were propagated via runner production after acclimatization, transplanted to pots and grown in a greenhouse. Culturing was done using the general method for 'Satsumaotome' in Kagoshima prefecture.

A decrease in survival rate was observed with increasing in dose; after 10 Gy and 45 Gy irradiation treatments with LETs of 48 and 23 keV/μm, respectively, the survival rate decreased to about half that of controls (Fig.1). Also, a decrease in plant growth was observed with increasing in doses; 10 Gy with 48 keV/μm and 40 Gy with 23 keV/μm produced many plants with decreased growth. Among the irradiation conditions with different LETs and doses, several interesting morphological alterations, in characteristics such as habits of growth and flowering, colors of leaf, pericarp and sarcocarp, and fruit shapes, were observed (data not shown). We selected mutation lines showing early flowering two years after the irradiation treatments (Table 1). Putative early flowering mutants were selected from all irradiation conditions tested. However, most selected lines also showed other differences from the originals. As a result, we selected two suitable early flowering mutants, which seem to retain the original fruit characteristic of 'Satsumaotome' after 20 Gy irradiation treatment with LET of 23keV/μm (Table 2).

Although fruit characteristics of the selected lines were similar to 'Satsumaotome', both mutants flowered 4 days earlier and their fruits ripened 7 days earlier than that of the originals.

The results obtained in this study revealed that C-ion beam irradiation may be effective for mutation induction of strawberries. Two putative early flowering mutants were continuously grown in the greenhouse and their detailed characterization is in progress.
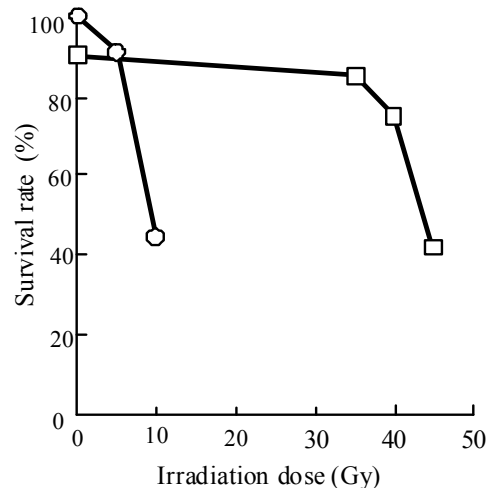
Fig. 1. Effect of C-ion beams on survival rate in 'Satsumaotome'. Data were recorded 20 weeks after the irradiations. LETs at the surface of samples were 23 (□) and 48 (○) keV/μm.

Table 1. Effect of C-ion beam irradiation on the selection of early flowering lines in 'Satsumaotome'.[a]

LET[b] (keV/μm)	Dose (Gy)	No. of lines planted	Early flowering lines selected (%)	
	0	78	0	(0)
23	10	196	5	(2.6)
	20	53	5	(9.4)
	30	126	6	(4.8)
48	5	149	5	(3.4)
	10	85	2	(2.4)

[a] Data were recorded two years after the irradiations.
[b] LETs were determined at the surface of irradiation samples.

Table 2. Characterization of early flowering mutants of 'Satsumaotome'.[a]

Lines	First flowering	First harvesting	Color of pericarp	Color of sarcocarp	Brix (%)
Satsumaotome					
	Nov. 8	Dec. 15	Light orange	White	9.7
B0401	Nov. 4	Dec. 8	Light orange	White	9.7
B0403	Nov. 4	Dec. 8	Light orange	White	10.3

[a] Data were recorded two years after the irradiations.

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An early flowering mutant of strawberry cultivar "Satsumaotome" induced by C-ion irradiation

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The strawberry cultivar "Satsumaotome" registered by Kagoshima prefecture has large fruits and good eating quality. But it is a late flowering cultivar, so the yield to the end of the year is low. Therefore we aimed to develop early flowering mutants which retain the original excellent fruit characteristics of "Satsumaotome" by ion beam breeding.

We determined optimum doses of C-ion irradiation based on the survival rate of the cultured tissue. From the mutants irradiated with C-ion beams (LET 23 keV/μm, 20 Gy) in 2004, we found one promising line B0401 which has a flowering date by 5 days earlier than "Satsumaotome". We are currently investigating the detailed characteristics of B0401. To find a line with even an earlier flowering date than that of B0401, we tried individual selection and line selection from the population irradiated with ion beams in 2005.

In 2005, we irradiated with C-ion beams (LET 23 keV/μm) at doses up to 20 Gy, targeting in-vitro cultured multiple buds derived from the shoot apex of "Satsumaotome". After the irradiations, we cultured to isolate mutants from chimera, and finally obtained 98 nursery plants. In 2006, we selected 16 individuals from the 98 plants based on their vigor and disease tolerance. In 2007, we propagated the selected 16 individuals to 8 stocks respectively, and planted them in a field for line selection. We investigated the plant habit, day of flowering, size and shape of fruits, and color of fruit peel and flesh, and selected a promising line.

One line (B0518) had an earlier flowering date, and two lines (B0513 and B0516) had a later flowering date than "Satsumaotome" (Table 1). The flowering date of B0518 was 20 days earlier and its number of days to flowering was 17 days shorter than "Satsumaotome" (Table 1). In terms of fruit characteristics, we found two variants (B0513 and B0517) whose fruit shapes were "long-conical" and "round" respectively, and whose peel color was "deep red". B0518 was not different from "Satsumaotome" in terms of the size of the fruit, predominant shape of the fruit, color of peel, and color of flesh (Table 2). As a result, we found that B0518 is a promising early flowering line which retains the original excellent fruit characteristics of "Satsumaotome". Next year, we plan to perform a more detailed investigation of B0518 characteristics with the eventual aim of registration as a variety.

Following the previous promising line B0401, we have selected the early flowering promising line B0518 which retains the original excellent fruit characteristics of "Satsumaotome". From the results, we concluded that ion beam breeding is effective for developing early flowering mutant lines of the strawberry cultivar "Satsumaotome".

Table 1. Flowering characteristics of mutant lines in 2007

Line Cultivar	Dose (Gy)	Flowering date (month/day)	Number of days to flowering (day)	SEM
B0501	10	11/23	52.0	1.4
B0504	10	11/27	54.9	0.8
B0505	10	11/24	52.8	0.7
B0506	10	11/21	50.1	1.5
B0507	10	11/22	54.5	4.4
B0509	20	11/23	51.3	0.3
B0510	20	11/21	49.1	0.7
B0511	10	11/26	53.8	1.1
B0512	20	11/24	51.3	2.5
B0513	20	12/13	75.0 **	4.2
B0514	20	11/23	51.0	2.2
B0515	20	11/20	47.9	1.4
B0516	20	12/27	85.1**	0.1
B0517	20	11/28	55.8	1.6
B0518	*20*	*11/12*	*41.5 **	*1.9*
B0519	20	11/24	50.6	2.2
Satsumaotome	—	12/1	58.4	1.0

Flowering date: 50% of plants at first flower

Number of days to flowering: Average number of days from planting to flowering

** indicates a significant difference from "Satsumaotome" based on Tukey-Kramer's Test (p<0.01)

Table 2. Fruit characteristics of mutant lines in 2007

Line	Fruit characteristics			
	Size	Predominant shape	Color of peel	Color of flesh
B0518	*large*	*conical*	*vivid red*	*whitish*
B0513	large	long-conical	deep red	whitish
B0517	large	round	deep red	whitish
Satsumaotome	large	conical	vivid red	whitish

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Breeding of a new Japanese barnyard millet variety with low amylose content and short-culm, by heavy-ion beam irradiation

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Japanese barnyard millet (*Echinochloa utilis* Ohwi et Yabuno) is considered to be one of the oldest cereal crops in Japan. In Iwate prefecture, Japanese barnyard millet has been cultivated as one of the main cereal crops, and as hay for horse feed, from ancient times. However, the millet cultivation area of Iwate has been rapidly decreasing since the late 1950's due to progress in upland field reclamation to paddy fields and the introduction of cold weather resistant rice varieties and industrial crops. For the last two decades, the nutritional value of millet has been reevaluated by home consumers. Due to this trend, the millet cultivation area and production of Iwate is increasing year by year. In particular, a large part of the national production of Japanese barnyard millet is produced in Iwate prefecture.

'Mojappe' is a local variety of Iwaizumi, a town located in the mountainous area of northern Iwate. It has good

Mojappe   Hie-Iwate 2   Daruma

Fig. 1   Culm length of new variety.

quality for eating because of its sticky starch with low amylose content. The amylose content of 'Mojappe' is about 12 to 13%, half that of other ordinary non-glutinous barnyard millets.[1,2] 'Mojappe' was adopted as a variety recommended for good flavor in Iwate prefecture in 2005. However, it has been hard to expand the cultivation area of this variety as much as it expected, because its culm length is too long to harvest with a head-feeding combine. Therefore, we tried mutation breeding of 'Mojappe' for mechanized production by means of culm length shortening.

Dry-seeds of 'Mojappe' were irradiated by C-ions accelerated to 135 MeV/u at a dose of 20 Gy at the RIKEN RI-beam factory in November 2003. The LET (linear energy transfer) range was 23 keV/μm. After irradiation, M_1 seeds were sown in a greenhouse of the Iwate Agricultural Research Center (IARC) in December 2003. About 5 months after the sowing, M_2 seeds were obtained. In 2004, M_2 seedlings were transplanted in an upland field of IARC, Northern Region Agricultural Institute. Seventeen out of 906 M_2 plants were selected for culm length after the heading stage. Harvested seeds of 17 selected M_2 plants were grown in a greenhouse during the M_3 generation in wintertime. In 2005, 17 M_4 lines originating from the selected M_2 plants were grown in a paddy field, and finally, only one line was selected as the shortest culmed mutant line. During 2007-2008, this line was evaluated for its yield, culm length, amylose content and other agronomic characters together with another mutant lines derived from gamma-ray irradiation. Eventually, this line was designated as 'Hie-Iwate 2.[3]

'Hie-Iwate 2' is shorter than 'Mojappe', but taller than 'Daruma', the leading variety of Iwate (Fig.1). However, we confirmed that a head-feeding combine could harvest 'Hie-Iwate2' in a paddy field test in 2008. Additionally, we expect that 'Hie-Iwate 2' is suitable for mechanical hulling and sawing with its awnless kernel.

We will apply for a official registration of 'Hie-Iwate 2' to the Ministry of Agriculture, Forestry and Fisheries of Japan within 2009.

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IV. OPERATION RECORDS

1. Operation of RIBF

Planning of RIBF operation

T. Suda, M. Kase, and T. Fujinawa

The operation of RIBF for FY2008 has been planed according to the approved budget for this fiscal year, plans for machine commissioning and construction and beam-time requests from experimenters.

According to the approved operation budget for five months, the operation plan of the new facilities, including the cyclotron cascade and BigRIPS/ZE, was made originally as :

  1) Two months in the period of April to June,
  2) Three months after the summer period.

No operation of the new facility was planned in the summer period, specifically from July to September, due to high electricity costs.

In February 2008, however, it turned out that there was a serious oil contamination problem in the refrigerators for SRC and BigRIPS. Detailed studies showed that its complete repair would take nearly half a year.

We, therefore, changed the operation schedule before summer. The time has been devoted into the developments of U and ^{48}Ca beams including the charge stripper development. As a result, the beam stability became remarkably better, and we were sure that the world's most intense ^{48}Ca beam would be provided for BigRIPS experiments when the refrigerators become ready.

The refrigerators have been completely fixed up in August, and they became operational immediately. A series of BigRIPS experiments using U and ^{48}Ca have been conducted for nearly two months during November and October.

In addition, the first SHARAQ commissioning was carried out using ^{14}N beam in the late March. A new beam line skipping IRC was installed and used for this experiment.

A long-term super-heavy search experiment to strengthen the evidence of our discovery of Z=113, more specifically ^{23}Na + ^{148}Cm -> ^{266}Bh + 5n was done for one month in October, and more than 40 days from Jan. 1 to the middle of February.

The other experiments at the "old" facilities were also scheduled and performed as much as possible based on the requests from spokespersons of the PAC-approved proposals. Even in the summer period, mainly in the weekends experiments were carried out.

In total, the accelerator has been operating 198.3 days for 78 experiments. The commissioning of the new facility was for 81 days. As a reference, the electric consumption profile of Nishina Center for FY2008 is shown in Fig. 1.
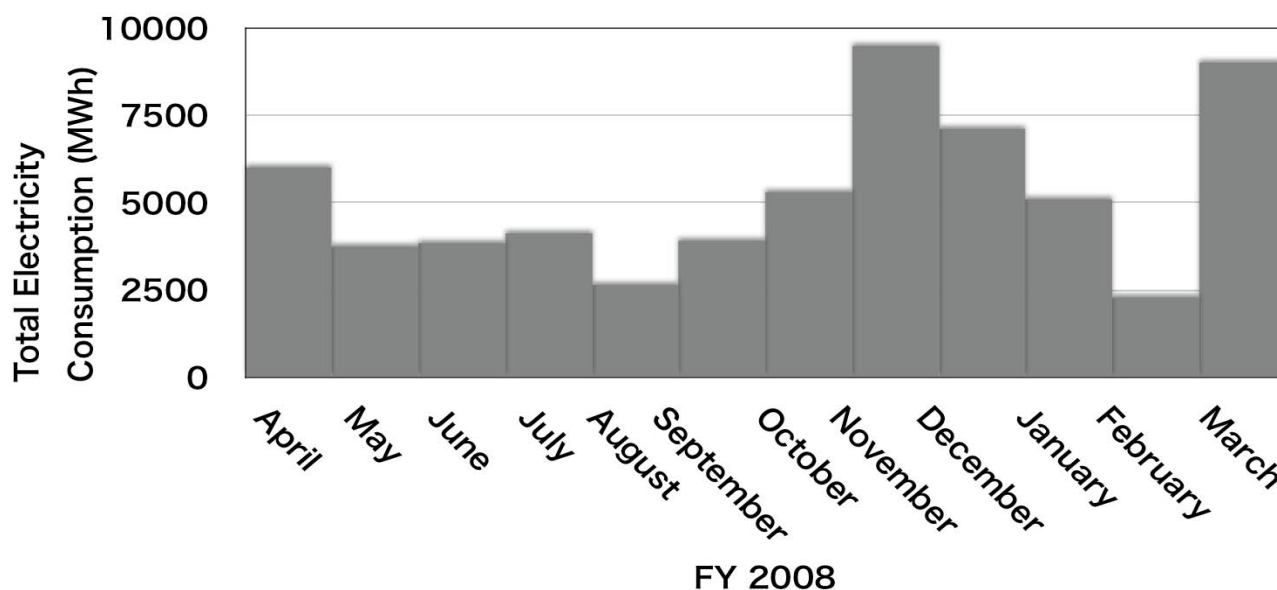
PAC Meetings for Nuclear Physics, and Material and Life Science

T. Suda, K. Ishida, and Y. Kobayashi

In 2007, RIKEN Nishina Center has established two Program Advisory Committees for reviewing submitted proposals in the fields of nuclear physics (NP-PAC) and material and life science (ML-PAC). Each PAC holds the meetings twice a year, and reviews the proposals.

The NP-PAC is co-organized by RIKEN Nishina Center and CNS, Univ. of Tokyo. The ML-PAC reviews experimental programs at RAL and RIBF.

NP-PAC

The NP-PAC meetings were held Feb. 18-19 and Nov. 20-21 this year[1]. The statics of the meetings are shown in Tabel 1.

ML-PAC

The ML-PAC meetings were held March 27-28, 2008 and Jan. 13-14 this year[2]. The statics of the meetings are shown in Tablel 2.

PAC members

NP-PAC : *W. F. Henning (ANL, the chair), J. Aysto (Univ. of Jyvaskyla), W. Mittig (MSU), Karlheinz Langanke (GSI) W. Lynch (MSU), D. C. Radford (ORNL), W. Liu (CIAE), A. A. Ogloblin (Kurchatov), B. Fulton (Univ. of York), A. Ohnishi (Kyoto Univ.), K. Yabana (Univ. of Tsukuba), I. Hamamoto (Lund Univ.), K. Imai (Kyoto Univ.), T. Noro (Kyushu Univ.), H. Okamura (RCNP), H. Miyatake (KEK), H. Sakai (Univ. of Tokyo)*

ML-PAC : *R. F. Kiefl (UBC, the chair), G. A. Beer (Univ. of Victoria), S. Ikeda (KEK), M. Iwasaki (RIKEN), R. Kato (RIKEN), K. Nagamine (UC, Riverside), N. Nishida (Tokyo Tech.), K. Nishiyama (KEK), F. Pratt (RAL), H. Takagi (RIKEN), J. Zmeskal (Stefan Meyer Inst.), F. Hanaoka (Gakushuin Univ.), T. Kameya (Tohoku Univ.), K. Komaki (Univ. of Tokyo), A. Shionohara(Osaka Univ.)*

References
1) http://www.nishina.riken.jp/UsersGuide/NP-PAC
2) http://www.nishina.riken.jp/UsersGuide/ML-PAC/

	3rd (Feb.18-19, 2008)				4th (Nov. 20-21, 2008)			
	Proposals		Days		Proposals		Days	
	requested	approved	Requested	approved	requested	approved	requested	approved
GARIS	0	0	0	0	0	0	0	0
CRIB	5	5	39	35.5	4	3	35	16
RIPS	6	5	53.5	29.5	2	2	19	19
BigRIPS/ZD /SHARAQ	7	6	70.7	44	6	4	58	30
TOTAL	18	16	163.2	109	12	9	112	65

Table 1. Statistics of the NP-PAC meetings held this year.

	3rd (March.27-28, 2008)				4th (Jan. 13-14, 2009)			
	Proposals		Days		Proposals		Days	
	requested	approved	Requested	approved	requested	approved	requested	approved
RAL	16	16	80	56	18	16	118	62
RIBF	3	3	30.5	25	3	3	43.5	25
TOTAL	19	19	110.5	81	21	19	161.5	87

Table 2. Statistics of the ML-PAC meetings held this year.

RILAC operation

Eiji Ikezawa, Ohki Tomonori,* Kase Masayuki, Takahide Nakagawa, Naruhiko Sakamoto,

Hiroki Okuno, Nobuhisa Fukunishi, Masaki Fujimaki, Makoto Nagase, Tadashi Kageyama, Shigeru Yokouchi,

Misaki Kobayashi-Komiyama, Masanori Kidera, Yoshihide Higurashi, Tamaki Watanabe, Kazunari Yamada,

Takeshi Maie, Hiroo Hasebe, Hironori Kuboki, Kenji Suda, Yutaka Watanabe, Toshimitsu Aihara,*

Hiromoto Yamauchi,* Akito Uchiyama,* Kazuyuki Oyamada,* Masashi Tamura,*

Akira Goto, Osamu Kamigaito, and Yasushige Yano

* SHI Accelerator Service Ltd.

Throughout this reporting period, RILAC has been in steady operation and has supplied various ion beams for various experiments and beam commissioning. Table 1 shows some statistics for RILAC operation from January 1 through December 31, 2008. The beam service time of RILAC accounted for 88% of the operation time of RILAC. The percentages of injection into RRC and the RILAC standalone were 43% and 57% of the total RILAC beam service time, respectively.

For beam commissioning and experiments of the RI Beam Factory (RIBF), 0.67 MeV/nucleon ^{238}U, 2.68 MeV/nucleon ^{86}Kr, and 2.68 MeV/nucleon ^{48}Ca ion beams accelerated by RILAC were injected intensively into the RIKEN Ring Cyclotron (RRC) 6 times in total from April through December 2008.

Table 2 shows a summary of the beam service time of the RILAC standalone allotted to each beam course (e2, e3, and e4) in the No. 1 target room of RILAC in 2008. This year, the e2 and e3 beam courses were used for the study of accelerator mass spectrometry and for research experiments on the heaviest elements, respectively.

Research experiments on the heaviest elements have been carried out since 2002. This year, the research experiments were carried out for 86 days from January through April, 25 days in June, 9 days in September, and 3 days in December.

Table 3 shows statistics for the operation times of an 18 GHz ECR ion source (18G-ECRIS) and a superconducting

Table 1. Statistics for RILAC operation from January 1 through December 31, 2008.

Operation time of RILAC	4578.0	hr
Beam service time of RILAC	4025.0	hr
Mechanical trouble	72.5	hr
Beam service time of RILAC standalone	2312.5	hr
Beam transport to RRC	1712.5	hr

Table 2. Beam service time of RILAC standalone allotted to each beam course in the No. 1 target room of RILAC in 2008.

Beam course	Total time (hr)	%
e2	101.0	4.4
e3	2210.5	95.6
e4	1.0	0.0
Total	2312.5	100.0

Table 3. Operation statistics for two ion sources (18G-ECRIS and SC-ECRIS) in 2008. These include preliminary work time. Operation times using SC-ECRIS are indicated in parentheses.

Ion	Mass	Charge state	Total time (hr)	
O	18	5	164.0 (	0.0)
Ne	22	5	223.5 (	0.0)
Na	23	5, 7	289.0 (	0.0)
Ar	40	11	42.0 (	0.0)
Ca	48	10	919.0 (	0.0)
Fe	58	13	371.0 (	0.0)
Zn	70	16	2044.5 (	0.0)
Kr	86	18	147.5 (	0.0)
Xe	136	20	223.5 (	0.0)
Os	188	24	80.5 (	0.0)
U	238	35	1650.0 (	0.0)
Total			6154.5 (	0.0)

ECR ion source (SC-ECRIS) in 2008. The ion beams of 11 elements were used in various experiments, beam acceleration tests, and beam commissioning.

We carried out the following improvements and overhauls during this reporting period.

1) The beam transport line between the 18G-ECRIS and the analyzing magnet was modified.
2) Flow switches for the lower-limit detection in the No. 2 rf power amplifier were replaced with new ones.
3) In the rf system for the No. 2 rf power amplifier, an auto gain controller and a pickup detecting the rf signal of the cavity was improved.
4) Automatic voltage regulators for all low level systems of the rf power amplifier were installed.
5) Plate power supplies at the final stages of the rf systems were subjected to annual inspection.
6) Two turbomolecular pumps of the FC-RFQ cavity and the No.1 RILAC cavity were replaced with cryogenic pumps. A turbomolecular pump was installed additionally at the beam transport line between the FC-RFQ cavity and the No.1 RILAC cavity. The other vacuum pumps were subjected to annual inspection.
7) Electron suppressers of the faraday cup at the beam transport line between the RILAC cavities were improved.
8) All water pumps of the water cooling system were subjected to a simple inspection.
9) The power supplies for dipole magnets (DMe1, DMe3, DMe4, and DMe5) will be replaced with new ones, because they were worn out from many years of operation. Each new magnet power supply is of the switching type and has a network IO (NIO) interface.

We experienced the following mechanical problems during this reporting period.

1) A cavity of the FC-RFQ was splashed with water due to a small hole in the cooling pipe of the outer wall of the cavity, and we repaired the part.
2) In the rf power amplifier system of the No.1 RILAC, power supplies for the filament of the final vacuum tube and for the plate of the driving vacuum tube had problems, and we replaced them with spare ones.
3) In the rf power amplifier system of the No.5 RILAC, a wide band amplifier and a driving vacuum tube had problems, and we replaced them with spare ones.
4) In the rf power amplifier systems of the CSM-A3 and the CSM-A4, power supplies for the plate of the final vacuum tube had problems, and we repaired them.
5) In the rf power amplifier system of the CSM-A5, a power supply for the control grid of the final vacuum tube had a problem, and we replaced it with spare one.
6) A magnet power supply of the miller-coil for the

18G-ECRIS was splashed with water due to a leak of a cooling pipe at an upper floor, and we repaired it.
7) A hard disk drive of the file server for the EPICS crashed, and another server system was used as a substitute for it. Later, all hard disk drives for the EPICS were replaced with new ones.

For the RI Beam Factory project, a high voltage terminal of the Cockcroft-Walton injector was remodeled and a superconducting coil system for the 28 GHz ECR ion source was installed on it. Thus, an 8 GHz ECR ion source (NEOMAFIOS), which has been used at the Cockcroft-Walton injector for many years, was removed. The beam transport line of the Cockcroft-Walton injector will be installed in parallel with the existing injection line of the FC-RFQ linac with two ECR ion sources.

AVF operation

M. Kase, T. Kageyama, N. Tsukiori[*2], Y. Ohshiro[*1], N. Fukunishi, T. Nakagawa, H. Okuno, N. Sakamoto,
M. Fujimaki, M. Kidera, M. Kobayashi-Komiyama, Y. Higurashi, M. Nagase,S. Yokouchi, K. Yamada,
H. Hasebe, K. Suda, H. Kuboki, T. Maie, K. Kobayashi[*2], M. Nishida[*2], Y. Kotaka[*2], S. Fukuzawa[*2],
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Table 1 shows the operation statistics of the RIKEN K70-MeV AVF cyclotron (hereafter denoted as AVF) in 2008 together with those in the preceding years. The total operation time in 2008 was almost the same as those in 2006 and 2007. The operation of AVF as the injector to RRC (AVF-RRC) has been at low level since 2006 because the RRC was frequently injected by RILAC for RIBF commissioning and experiments. The total operation time of 2008 in the AVF stand-alone increased by 8% compared with that in 2007 but did not reach the level of 2006.

About 60% of the total AVF operation time in 2008 was dedicated to CRIB experiments managed by CNS. Eleven experiments were carried out at the CRIB. Two kinds of solid material ion beams, Si and Li, were produced in the Hyper ECR ion source and delivered to the CRIB.

It is now the 7th year since the educational physics experiment for university students commenced based on the RIKEN-CNS collaboration agreement. Four sets of one-day experiments on the elastic scattering using a 6MeV/u α-beam were performed in Autumn at the vacuum chamber on the way to the CRIB.

The E7b beam line which is for general purposes was used six times in 2008. Four of them were for the experiments on the electrochemistry of seaborgium using boron, oxygen and neon beams on a ^{248}Cm target. Since 2008, a new category of beam time for the detector-development was allocated officially for the first time. Two test beam times for detector development were carried out in C03 and E7b.

The C03 target station was used six times for RI productions for charged distribution, which had been routinely performed since late 2007. Radio-nuclides of ^{65}Zn and ^{109}Cd are produced using a 14MeV proton beam and delivered to outside RIKEN via Japan Radioisotope Association. The experiments to study αfine structure of lawrencium isotopes were also performed at C03 using nitrogen beams on a ^{248}Cm target twice in November 2008.

In November, a problem related to the pumping of cooling water for ion source caused the cancellation of a scheduled experiment. This was eventually compensated in December.

Table 1. Statistical data of AVF operation in 2006 – 2008.

Year	2006	2007	2008
Total operation time	3963 hr	3669 hr	3648 hr
Beam tuning	853 hr (22 %)	767 hr (21 %)	686 hr (19 %)
Injection to RRC	1051 hr (27 %)	1235 hr (34 %)	1165 hr (32 %)
AVF stand-alone	2059 hr (52 %)	1667 hr (45 %)	1797 hr (49 %)
Beam course (AVF stand-alone)			
E7a (CRIB)	1275 hr (62 %)	1289 hr (77 %)	1119 hr (62 %)
E7b	257 hr (12 %)	0 hr (0 %)	228 hr (13 %)
C03	527 hr (26 %)	378 hr (23 %)	450 hr (25 %)

Some of the contact fingers of No.1 rf resonator were burnt due to trouble in the driving part of the air cylinders pressing on the coaxial part of the resonator. During the Summer overhaul period, the levels of the two rf dee electrodes were re-adjusted using a special jig, since over the years they had sunk down from the median plane by 4 mm at the maximum over a long period of time.

Beam studies were performed on a few ion beams. First, the acceleration test for 14 MeV protons was

carried out aiming at obtaining higher intensities to meet the requirement for RI production. By precisely tuning the injection and extraction systems, an intensity of 30 μA became available. Next the acceleration tests to increase the attainable maximum energies of $^{16}O^{7+}$ and $^{6}Li^{3+}$ ions were carried out. The maximum energies of these ions had been limited by the available dee voltages, which are lower than the required ones in correspondingly high frequencies. Recent simulations, however, showed that these energies could be increased even with these available voltages by adjusting the injection beam phase and the trim coils currents in the central region to enable a beam to clear the channel immediately after the exit of the inflector. In these tests, the maximum energies of $^{16}O^{7+}$ and $^{6}Li^{3+}$ ions were actually increased from 10 to 11 and from 9.5 to 11.2 MeV/nucleon

A new hot lab has quickly become necessary when the RI material produced at the C03 target station is treated chemically because the previous hot lab in the basement of the Nishina Building was far too busy for the new RI distribution, for the preparation of uranium material in the ion source as well as for the ordinary radiochemical research. Taking into account of the convenience of the shortest distance of RI transportation, the site right above the C03 with a direct distance of 6 m in the polarized ion-source room was selected as the location of the new hot lab. In order to make the space for new hot lab, the previous 10GHz ECR ion source was replaced by the super-conducting ECR ion source that is more powerful and compact. The new ion source which belongs to CNS was installed in the Summer of 2008 after the 10 GHz ECR ion source which had been used for twenty years, was handed over to Tohoku University in June 2008. During the conversion of the ion sources, the Hyper ECR was the only ion source for AVF. Due to the shortage in preparation time, it failed to deliver enough intensities for the ^{28}Si and ^{58}Ni beam.
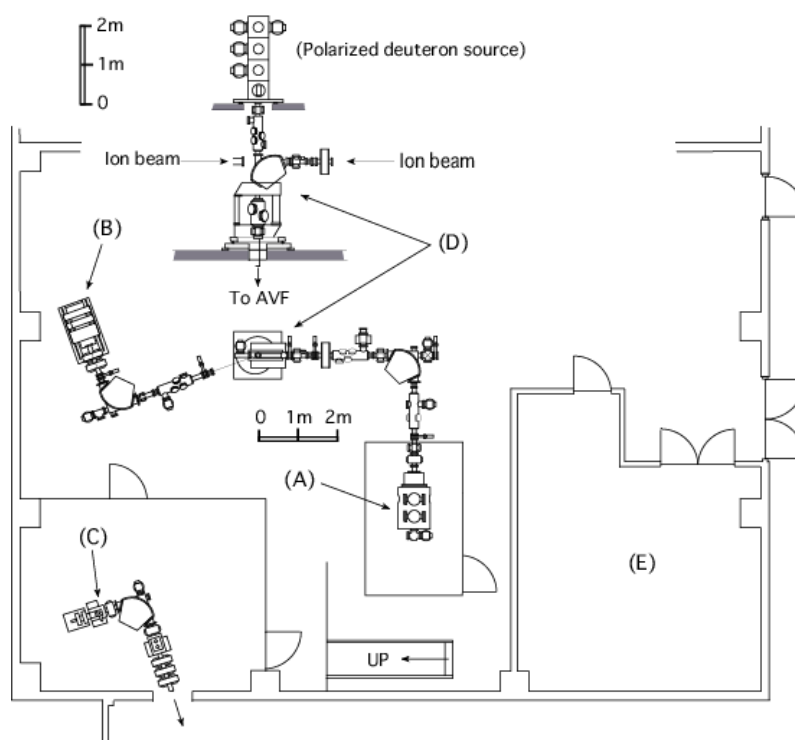
Fig. 1. The new layout of the polarized-ion-source room. The 14GHz super-conducting ECR ion source (A) was installed in place of the old 10GHz ECR ion source. A new hot lab (E) is just above of the C03 target station. (B) is Hyper-ECR ion source and (D) is the rotating magnet for switching the two ECR ion sources. The polarized deuteron source, which is on second floor and is not shown in the figure, is same as before and is now ready for supply the 250 MeV polarized deuteron in the spring of 2009. (C) is the CAPRIS (ECR ion source) which is used for the atomic physics reserches

Charged Distribution of Radioisotopes Produced at AVF Cyclotron

T. Kambara, H. Haba, Y. Ezaki, K. Takahashi, and H. Miyamoto

RIKEN Nishina center started fee-based distribution of radioisotopes (RI's) in order to contribute to the general public in Japan through accelerator technologies.

RIKEN has a long history of production and application of RI's at its cyclotrons since the first cyclotron was build in 1937. At the present AVF cyclotron, 19 nuclides with relatively long lifetime have been produced and used for experiments.[1] Based on its historical background and accumulated know-how on RI production, RIKEN Nishina Center has started fee-based distribution of two nuclides, ^{65}Zn ($T_{1/2}$ = 244 days) and ^{109}Cd ($T_{1/2}$ = 463 days), to the general public. These nuclides were previously supplied by private companies but recently they terminated the supply, although there is still demand.

Distribution is carried out in collaboration with the Japan Radioisotope Association[2] (JRIA), an organization of RI users and research workers which maintains a complete system from supply to disposal of RI's in Japan. Transactions are based on a Material Transfer Agreement between JRIA and RIKEN which went into effect in October 2007. Requests for RI's can be sent from inside of Japan through JRIA (FAX 03-5395-8055, E-mail: gyomu1@jrias.or.jp). The chemical form can be selected from solutions of hydrochloric acid, acetic acid, nitric acid or isotonic sodium chloride, between 0.1 mL and 3 mL. Details are found in the on-line ordering system J-RAM[3] of JRIA. Normally the RI's are distributed 10-16 days after the acceptance of the order. In 2008, we accepted 6 requests for ^{109}Cd and distributed total amount of 33 MBq, and 7 requests for ^{65}Zn and distributed 34.7 MBq.

The nuclides are produced at a beam line of the AVF cyclotron dedicated to RI production, ^{65}Zn is produced by the reaction ^{65}Cu(p,n) with a metallic copper target and ^{109}Cd by the reaction ^{109}Ag(p,n) with a silver target. The beam energy from the AVF cyclotron is 14 MeV and intensity is about 15 μA. The target is a stack of two disks with diameter of 10 mm and thickness of 0.125 mm each, purity of 99.99 % and natural isotopic composition. The target is cooled by water and He gas during irradiation which lasts about 2 days. After the irradiation, ^{65}Zn is separated by an ion-exchange method and ^{109}Cd by the AgCl precipitation and ion-exchange method.

Examples of the quantity and quality of the nuclides of our RI's are as follows: In the case of ^{65}Zn, an amount of 73 MBq was produced in 41 hours of irradiation and 99 % of it was separated by the chemical processing, and in case of ^{109}Cd, an amount of 16 MBq was produced in 36 hours of irradiation and the chemical yield was 74 %. The impurities as well as the specific activities of the purified RI's were evaluated using ICP-MS. As an example, the specific activities of ^{65}Zn and ^{109}Cd were 410 and 340 kBq/ng, respectively.

The next nuclide candidates of fee-based distribution are ^{75}Se ($T_{1/2}$ = 120 days) and ^{88}Y ($T_{1/2}$ = 107 days) and the production and separation techniques are being developed.

We are also studying the production and application of short-lived RI's with a gas-jet transport system.[4] The target chamber of the gas jet system is installed in front of the target for the production of ^{65}Zn and ^{109}Cd, so the long- and short-lived RI's are produced in parallel with the same beam.

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The operations of the RIBF ring cyclotrons

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The RIBF accelerator complex consists of four ring cyclotrons (RRC, fRC, IRC, and SRC) together with two injectors (RILAC and AVF). Although there are many acceleration modes, the RRC always works as the first booster ring cyclotron in every acceleration mode. Figure 1 shows how every ring cyclotron operated in 2008 on a basis of RRC Yearly operation-time, 3961 hr in 2008. About half of them were spent for the RIBF accelerations; 30% for the fixed-frequency acceleration mode of a ^{238}U beam with an energy of 345MeV/u and 20% for the variable-frequency acceleration mode of a ^{48}Ca beam with the same energy.

In early 2008, the BigRIPS experiments using the ^{238}U beam with 345MeV/u had been scheduled in spring. However trouble with oil contamination was found in February inside the BigRIPS and SRC cryogenic systems one after another and after following investigations, it turned out that the problem was so serious that it will take several months to sweep all the problems completely. Then it was decided in April that the BigRIPS experiments were shifted in autumn.

During the improvement of the SRC cryogenic system, machine studies were performed for the ^{238}U and ^{48}Ca beam accelerations without the SRC, focusing on checking of stripper foils, improving beam monitors, conditioning many rf cavities, establishing precise isochronous magnetic field in each ring cyclotron, stabilizing all the parameters of the accelerators including the injector RILAC etc.

The experiments of BigRIPS were reshcehduled and carried out in November for ^{238}U beam and in December for ^{48}Ca. The beam parameters during the experiments are summarized in Table 1. In 2008, the acceleration parameters were dedicated for one frequency of 36.5 MHz in the IRC and the SRC, giving a final energy of 345MeV/u

Table 1 Beam parameters of RIBF experiments in 2008

Beam	Energy (MeV/u)	Period (days)	Beam intensity (pnA)	Supply eff. (%)
^{238}U	345	18.3	0.1 − 0.4	75
^{48}Ca	345	11.5	100 − 170	59
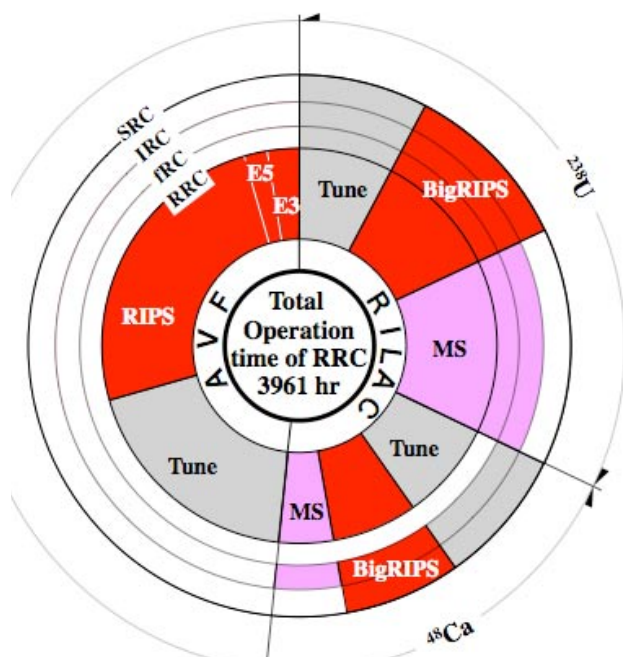
Fig. 1. The operation statistic in 2008 of every ring cyclotrons in the RIBF on basis of the RRC. The total operation time of RRC was 3961 hr, corresponding to 360 deg of the circle graph. "Tune" is the beam tuning for experiments, "MS" the machine study. The dark portions with white letters are the experiments, BigRIPS in RIBF and RIPS, E5, E3 in the Nishina Building.

only.

In the BigRIPS experiments, the ^{238}U beam was used for the Zero Degree Spectrometer commissioning and also for the new isotope search, resulting in a discovery of more than twenty new isotopes. The ^{48}Ca beam was used for the research for the nuclear structure and the gamma spectrometry. During the ^{238}U beam time, the beam intensity became larger and larger and finally reached to 0.4pnA. The operation became gradually stable and in the last few days of the experiment, the beam stayed on the BigRIPS target more than 90% of the available time. On the other hands, during the ^{48}Ca beam time, several problems occurred and frequently interrupted the experiments, although the beam intensity reached a value (170pnA) more than expected. The cooling system of the beam monitor was paralyzed twice, probably due to a high irradiation of fast neutrons on its flow sencers. The plate power supply to one of the rf amplifier for the SRC resonator, RES1 was turned off due to an error of interlock circuits. One of the SRC resonators, RES3, had a problem inside and became unusable during the second half of the beam time. A wide band amplifier for a flat-top system of SRC had a problem in its output directional coupler. The total interruption time amounted to more than eighty hours.

About half of the RRC operation time was used on ordinary experiments in the Nishina Building as listed in Table 2. A total of 1000 hr was spent on six kinds of RIPS experiments, including the development of ion-trapping technology, which was performed four times. The experiments for the biological research were still so active that a total of 89 hr were spent on them by using the three kinds of beams ^{12}C, ^{40}Ar and ^{56}Fe ions and repeating 17 times on a regular basis in the E5 target room. In the E3 target room, the following experiments were carried out; the RI productions for multi-tracer, the simulation of single event in electronic devices against irradiation of cosmic ray, and the calibration of the radiation detector for cosmic ray.

In August, one of the RIPS experiments using ^{28}Si beam was interrupted for a half day due to an instantaneous power failure caused by a thunderbolt hitting a power facility near by. In the RIPS experiments using a beam of solid ions, ^{28}Si and ^{58}Ni, the enough beam intensities could not be supplied under a lack of preparation time of ion source due to an exchange of AVF ECR sources.

Table2 The experiments using the RRC beams in 2008

Beam Course	No. of allocation	Beam & Energy	Total Hours	Proportion
E6(RIPS)	12	^{13}C–135MeV/u ^{28}Si–135MeV/u ^{36}Ar–115MeV/u ^{40}Ca–90MeV/u ^{58}Ni–90MeV/u	987	85%
E5b	17	^{12}C–135MeV/u ^{20}Ne–135MeV/u ^{40}Ar–95MeV/u ^{56}Fe–90MeV/u	81	7%
E3b	3	^{14}N–135MeV/u ^{40}Ar–95MeV/u ^{84}Kr–70MeV/u	97	8%
		Total	1165	100%

Status of RIBF control system and beam interlock system

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We report three developments of the RIBF control system. The first is development of useful software used in the recent fine tuning of the cyclotron complex. The second is performance testing of our beam interlock system (BIS). The third is introduction of a new EPICS-embedded system on F3RP61-2L. Our work is crucial for providing high power beams for RI-beam production at BigRIPS.

New software was developed to visualize data measured by differential probes installed in our cyclotrons. The radial pattern of the accelerating beam in the cyclotron is obtained by measuring beam current with a thin electrode called a differential probe. The radial distribution of the beam is strongly affected by cyclotron parameters such as the RF phase of flat-top cavities. The new radial-probe software has the following functions:

- Zooming in or out of the graph on both the X and Y axes.
- Automatically indicating the numerical coordinates of the mouse pointer on the graph. This function is used to measure turn separation.
- Saving raw data in a numerical table format.
- Leaving the measured data on the graph in shadow. We use this function to compare the most recent data with previous or a stored data.
- Selecting whether to display or hide the data from each measurement finger of the radial probe.

Fig. 1 shows data measured by the IRC-MDP2 during a ^{48}Ca experiment. Thanks to the new functions mentioned above, precise tuning of the RF phases and voltages of accelerating and one flattop cavities was done using the new radial probe graph software. This worked effectively to reduce beam losses in the cyclotrons during beam tuning.
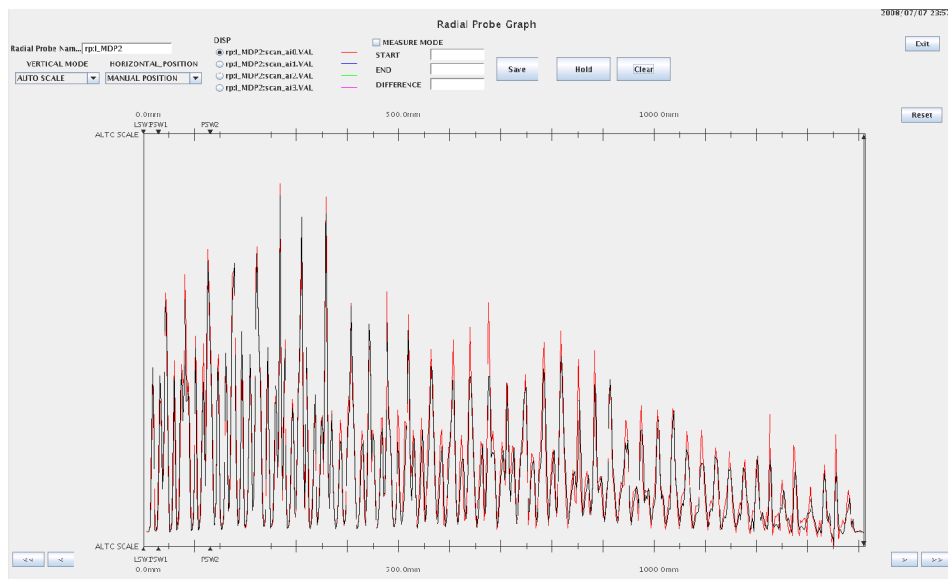
Fig. 1.   Beam pattern in the IRC measured by IRC-MDP2 with reference data.

In addition, we created many new GUIs to support cyclotron operators. For example, we prepared a bar-graph type GUI to simultaneously show beam intensities lost at the selected baffle slits placed at the entrance or exit of magnetic or electric channels of cyclotrons. It was very helpful to know positions where beam losses took place. The information on beam intensity is also transferred to the BIS, whose purpose is to protect cyclotrons from serious beam losses.

The BIS is a beam interlock system to protect various devices in accelerators and their beam transport lines from irradiation by excess beam.[1] It turns on a beam chopper placed at the exit of an ion source when the system senses a safety alarm signal from devices. To definitely ensure that a beam is shut off, the system simultaneously sends a signal to insert a Faraday cup located upstream of the sensed device. In the current state, many alarm signals are connected into the BIS: breakdown of RF control, errors of magnet power supplies, vacuum systems, temperature monitor system of SRC, doors of each experimental cave,

and so on. In addition to digital alarm signals, the BIS can stop a beam by setting a threshold for analog data measured by beam baffle slits in cyclotrons. Three BIS were installed to the RILAC area, the RRC and fRC area, and the IRC and SRC area. The BIS is a system based on PLCs. Each BIS has 5 PLC stations except for RILAC one (3 stations). Optical fiber cables connect among them and 5 PLC stations constitute one loop structure. Each safety alarm signal and output signal is connected into the I/O module in each station. The BIS was introduced into the RIBF in 2005. The BIS debugging processes have been conducted in the three subsequent years. Recently the beam power from SRC was greatly increased, for example to 3 kW for a ^{48}Ca beam. It is essential for each BIS to properly carry out its function of preventing destruction of cyclotrons by high beam power. This year we improved the circuit of a beam chopper used in BIS. During the experiments, all BIS worked perfectly, i.e.; the beam chopper and Faraday cups stopped the beam without exception after receiving alarm signals or signals caused by threshold-over beam losses. This implies that BIS is now finished. The remaining problem is that the programmed logic for the action of the beam chopper is not correct. The program for the action of the beam chopper will have to be improved in 2009.

Last are new developments this year in our EPICS-based control system. Many PLCs have been adopted in the RIBF control system. They implement various control logics on themselves and control devices such as radial probes of cyclotrons, vacuum systems of cyclotrons, and so on. Most are controlled or monitored in the EPICS-based control system. In order to control PLCs on EPICS, PLCs need to be connected with EPICS Input/Output Controllers (IOCs) through Ethernet connections to convert the communication protocols (EPICS Channel Access protocol and the proprietary communication protocol of each company's PLC). If it is possible to run EPICS IOC programs on the PLC CPUs themselves, that is a more cost-effective and convenient solution for us. The reason is that this eliminates the need to install a PC for running IOC programs, and was can just create control programs with EPICS sequencers only instead of creating ladder programs for PLCs and EPICS sequencers for IOC. At the beginning of this year, Yokogawa Electric Corporation developed a new CPU module running Linux which can function with a base module and I/O modules of FA-M3 PLC, F3RP61-2L.[2] We started to develop embedded EPICS on F3RP61-2L in collaboration with the KEK control group and successfully complete the development in June.[3] It is expected that introducing F3RP61-2L will make our control system simpler and easier to maintain. In July, we successfully controlled a test switch box with some push buttons and indicators using F3RP61-2L. Furthermore, we recently succeeded in setting and reading an analog value to a test system. Fig. 2 shows a PLC test system with a F3RP61-2L. In J-PARC (KEK), F3RP61-2Ls have been used to control power supplies and the motion of septum magnets and beam diagnostic devices in the slow extraction line of the J-PARC Main Ring. Encouraged by the results, we plan to

introduce the embedded EPICS on F3RP61-2L into the following newly installed and current systems:

- Control system of CNS super-conducting ECR ion source.
- Control system of a new super-conducting ECR ion source of RILAC Ⅱ.
- Control system of the injection buncher, RFQ, and rebuncher of RILAC.
- Control system for motion control of Faraday cups of RILAC.[4]

We have already made the system for the third system above, and will try to introduce it in February 2009. Furthermore, we have started developing control systems for the first two systems with the aim of using them in early 2009.

Fig. 2.   F3RP61-2L (the second from left module) in a test system.

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Water Cooling System of Accelerator for RIBF

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The water cooling system for the RI Beam Factory (RIBF) was newly constructed in 2004. Photographs of the water-pumps and the cooling towers are shown in Fig. 1, Fig. 2, Fig.3, and Fig. 4. A block diagram of the water cooling system is shown in Fig. 5. There are seven categories as follows ; the No.1 cold-water circuit(CW-1), the No.2 cold-water circuit(CW-2), the No.2 Cooling-tower circuit (CT-2), the No.3 Cooling-tower circuit(CT-3), the No.4 Cooling-tower circuit(CT-4), the Sub-system and the cooling system for the fixed-frequency Ring Cyclotron (fRC).

The precise temperature control function adheres to the fRC Cooling system, supplying the controlled water at ±0.1degree to each main and trim coil.

The system was designed to save energy. In every water-pump in these systems, a highly effective motor with an efficiency of 93.5% is used, as shown in Fig.1, compared to a normal motor with an efficiency of 91%. In addition, the use of low-noise and low-vibration devices together with inverter circuits is also effective.

Fig. 2.   Photograph of the Cooling Towers on the rooftop.

Fig. 3.   Photograph of the Cooling water-pump on the first floor.

Fig.1. Photograph of the Water-pump with highly effective motor.
（ JIS Standard C4212 ）

Fig.4. The Sub-system cooling pump.（IRC room on the second floor in the basement）
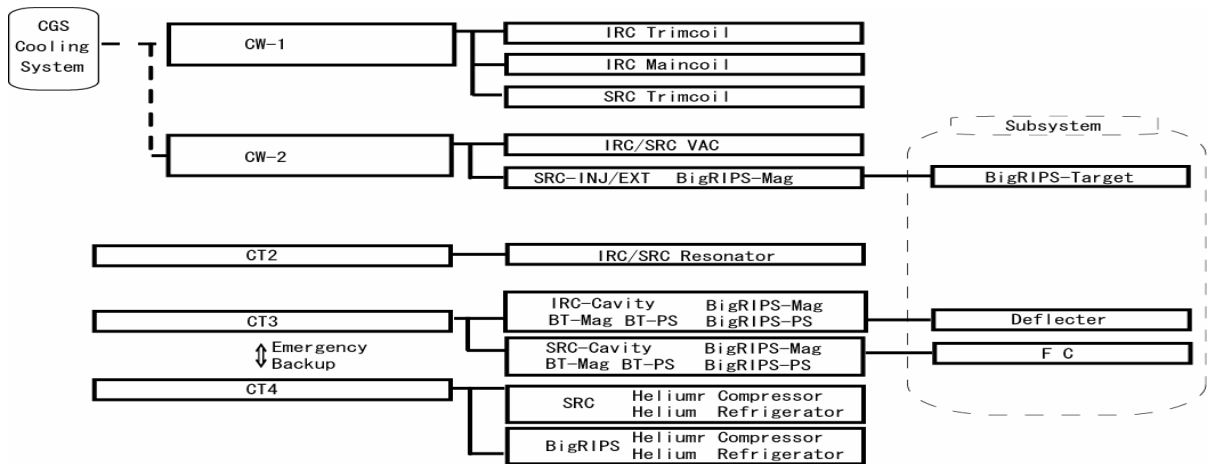
RRC: RIKEN RING Cyclotron, fRC: fixed-frequency Ring Cyclotron,

IRC: Intermediate-stage Ring Cyclotron, SRC : Superconducting Ring Cyclotron

Fig. 5. Schematic diagram of the Water-Cooling System of the Accelerator for RIBF

The total operation time of the water-cooling system in fiscal year 2008 was 120 days due to oil-contamination trouble in the SRC and BigRIPS helium refrigerators.

In December, during the beam time, the water pump (P-13) in the sub-system stopped twice due to a failure of its control circuit. It may have been by the high-level radiation of fast neutrons from a beam line. One of the system water-flow sensor which was being irradiated, made an error signal. The sensor will be moved far from the beam line in 2009.

Because the systems CT-2 and CT-3 supply water to various equipment, there is frequently a lack of water flow in some equipment. Fine adjustment of water-flow division is always an important and hard task when new equipment is installed.

The construction of the cooling system for the new injector (RILAC II) was designed as shown in Fig. 6. The new system will use cold water from CGS system as much as possible.
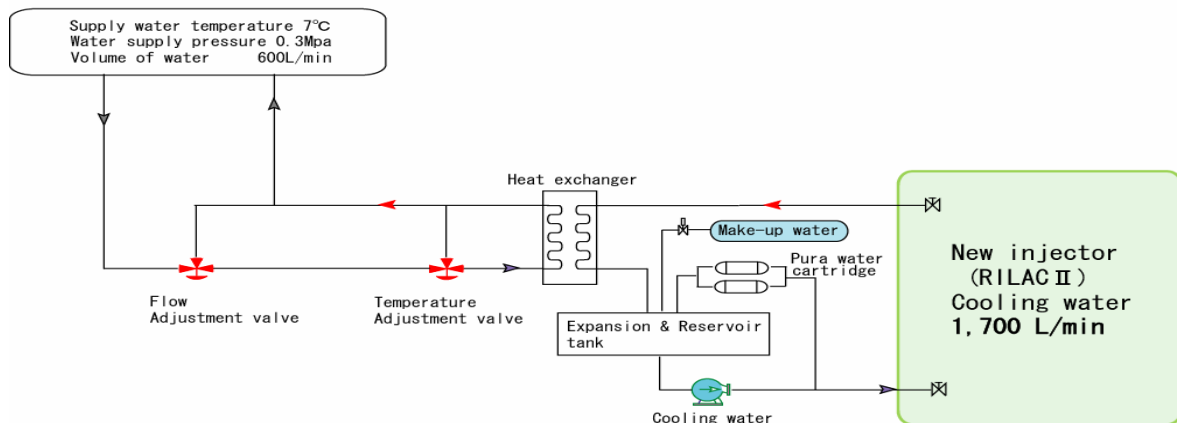
Fig. 6. Schematic diagram of the cooling system for RILAC II

Radiation Safety Management at RIBF

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Residual radioactivity at the deflector of the AVF cyclotron was measured to be 12.5 mSv/h on December 4, 18 hours after an operation with a 6.2 MeV/u 300 pnA ^{20}Ne beam. We did not have an opportunity to measure the RRC deflector in 2008. Figure 1 shows the variation in the dose rates at these deflectors since 1986. The beam intensity of AVF was increased for the radioisotope production and the dose rate incresed again.

The residual radioactivity was measured along the beam lines after almost every experiment. Spots 1–31, marked with solid circles in Fig. 2, are the places where high dose rates were observed. Table 1 shows these dose rates together with the measurement dates, beam conditions and the decay periods following the end of an operation. The maximum dose rate was found to be 5.2 mSv/h at point 29 on the surface of G01 Faraday cup after SRC.

We continuously monitor the radiation in and around the RIBF facility by using neutron and gamma area monitors. The results at the site boundary (No. 1-4 posts) and at the computer room of the Nishina building which is the boundary of the radiation controlled area are shown in Fig. 3. The values are the average dose rates of each day including natural background radiation. No. 1 post is close to the Wako Daiyon Elementary School, No. 2 is in front of the Nishina building, No. 3 is close to Route 254 and No. 4 is close to the BSI Central Building. The computer room is on the ground floor immediately above a bending magnet that guides the beam from the RRC vault to the distribution corridor.

Due to the constant natural gamma radiation from the building structure, the gamma dose rate at the computer room is high and stable, the computer room's neutron dose, however, is low because of the shielding effect of the building against the cosmic neutrons and as a result of it being strongly affected by the accelerator operation.
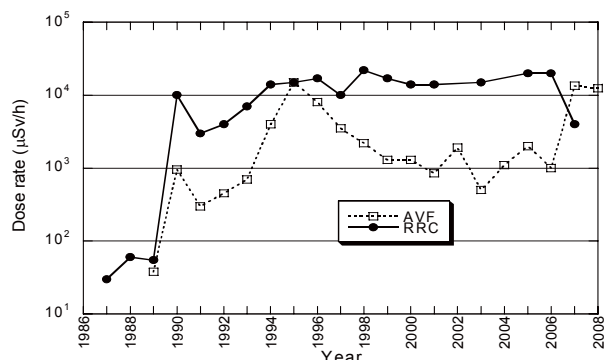
Fig. 1. Dose rate at the deflectors of RRC and AVF since 1986. Dose rates were not measured at RRC in 2002, 2004 and 2008.

No accelerator was operated between August 19 and September 13, and the dose rates at this period were assumed to be natural background. The net accumulated dose, i.e., the dose after the subtraction of background, at the computer room in 2008 was 3.5 μSv which was much lower than the legal limit (5 mSv/y). The annual dose since 1999 is shown in Fig. 4. The value increased until 2005 and decreased after that due to the operation condition of RRC.

The net dose rates at the site boundary are very small, because the influence of the accelerator operation is tiny, owing to the long distances and the thick shields. The net accumulated dose at any point was smaller than the detection limit, which was assumed to be one standard deviation; 8 μSv/y for gammas and 2 μSv/y for neutrons. In any case, the annual dose at the site boundary was much lower than the legal limit (1 mSv/y).

Table 1. Dose rates measured at beam lines in 2008. Points 1-31 indicate measured locations shown in Fig. 2.

Point	Dose rate (μSv/h)	Date (M/D)	Particle	Energy (MeV/u)	Intensity (pnA)	Decay period (h)
1	280	8/14	Si-27	135	6	173
2	1200	8/14	Si-28	135	6	173
3	550	8/14	Si-28	135	6	173
4	45	8/14	Si-28	135	6	173
5	550	6/10	Ca-48	114	68	24
6	42	6/10	Ca-48	114	68	24
7	40	6/10	Ca-48	114	68	24
8	13	6/10	Ca-48	114	68	24
9	18	6/10	Ca-48	114	68	24
10	25	8/14	Si-28	135	6	173
11	18	8/14	Si-28	135	6	173
12	40	8/14	Si-28	135	6	173
13	50	8/14	Si-28	135	6	173
14	40	8/14	Si-28	135	6	173
15	750	8/14	Si-28	135	6	173
16	150	8/14	Si-28	135	6	173
17	40	5/2	U-238	114	2	3
18	18	5/2	U-238	114	2	3
19	27	6/10	Ca-48	114	68	24
20	250	6/13	N-14	135	500	293
21	45	6/13	N-14	135	500	293
22	13	5/2	U-238	114	2	3
23	14	6/10	Ca-48	114	68	24
24	23	6/10	Ca-48	114	68	24
25	12	12/24	Ca-48	345	160	109
26	1300	6/10	Ca-48	114	68	24
27	700	6/10	Ca-48	114	68	24
28	130	12/24	Ca-48	345	160	80
29	5200	12/24	Ca-48	345	160	80
30	200	12/25	Ca-48	345	160	109
31	950	12/25	Ca-48	345	160	109

*1 Japan Environment Research Corp.
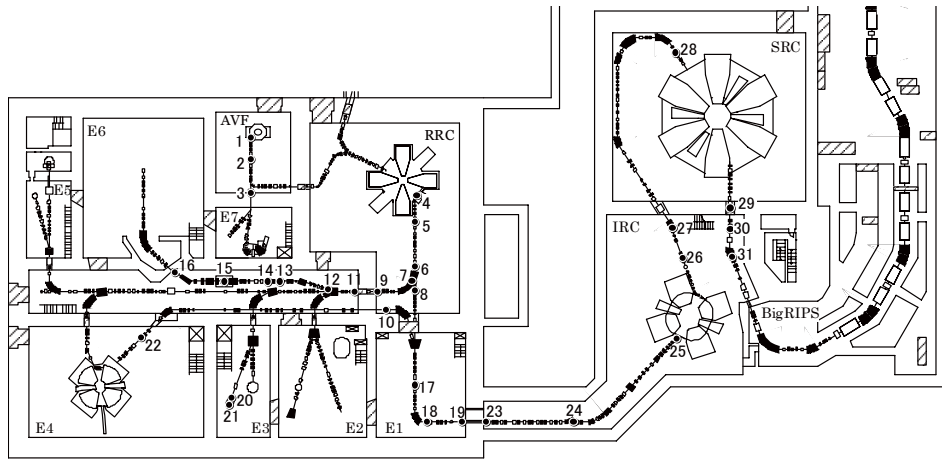
Fig. 2. Layout of beam lines at RIBF. Locations where high residual radioactivity was observed are indicated by solid circles, 1-31.

The water in the closed cooling systems at BigRIPS was sampled after the operation with an intense 345-MeV/u ^{48}Ca beam in December, 2008, and radionuclide concentrations were measured by using a liquid-scintillation counter and a Ge detector. The results are shown in Table 2. The concentration of the cooling water used at the side-wall beam dump was highest, but the sum total of the ratios of the concentrations to the legal limits for the drain water over all the radionuclides is still much smaller than unity. We will monitor these concentrations, and release the water before they exceed the legal limit.

Radiation surveys in and around the RIBF building were also performed by using hand-held detectors during the accelerator operation with the ^{48}Ca beam in December, 2008. At the boundary of the radiation controlled area, the highest dose rates of 0.7 µSv/h for neutrons and 0.2 µSv/h for gammas were observed at the He compressor room on the 1st floor of RIBF accelerator building. In the radiation controlled area, streaming radiations through the air duct from IRC vault caused the highest dose rate of 210 µSv/h for neutrons and 40 µSv/h for gammas at the He refrigerator room on the 1st basement floor. The streaming from SRC vault was found to be as small as 1.5 µSv/h for neutrons and 4 µSv/h for gammas.
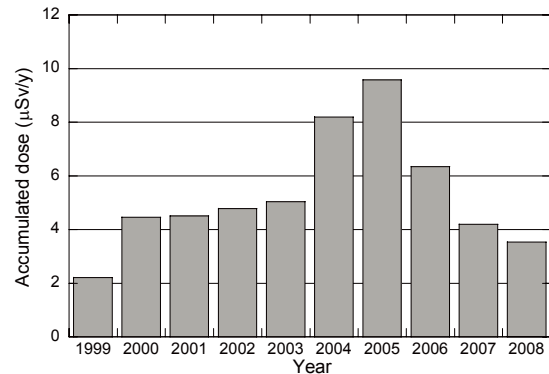
Fig. 4. Accumulated leakage radiations at the computer room of Nishina building since 1999.
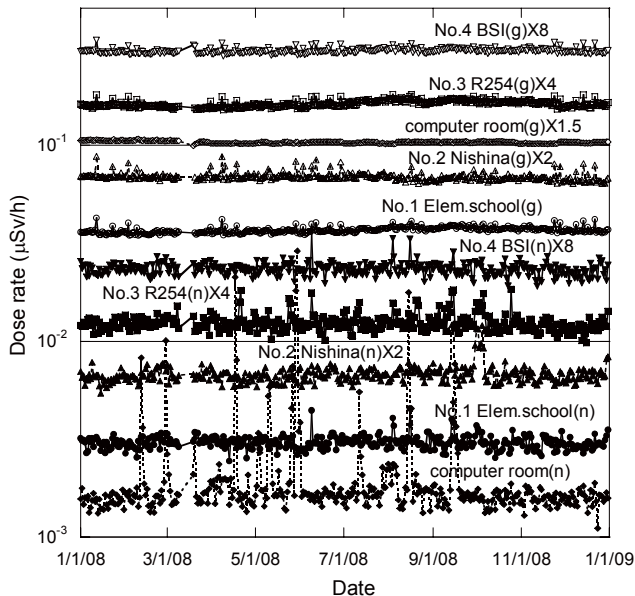
Fig. 3. Daily averaged dose rates in 2008 at the site boundary (No. 1 through No. 4) and at the computer room of the Nishina building. (g) and (n) represent gammas and neutrons, respectively, and "×2", for example, means the values are multiplied by 2.

Table 2. Radionuclide concentration in cooling water of BigRIPS at January 7, 2009, the legal limits for drain water, and the ratio of the concentration to the limit.

cooling water	nuclide	concentration (Bq/cm^3)	limit	ratio to limit
F0 target	H-3	-[1]	60	-
Exit beam dump	H-3	1.7e-1[2]	60	2.9e-3
Side-wall beam dump	H-3	3.5e-1	60	5.8e-3
	Be- 7	9.5e-1	30	3.2e-2
	Co-57	6.4e-4	4	1.6e-4
	Co-58	3.7e-3	1	3.7e-3
	Mn-52	5.3e-4	0.5	1.1e-3
	Mn-54	5.4e-4	1	5.4e-4
	Mn-56	7.8e-4	3	2.6e-4
	Na-22	5.8e-4	0.3	1.9e-3
	Ca-47	1.5e-3	0.5	2.9e-3
			summation	4.8e-2

1) lower than detection limit.   2) read as $1.7×10^{-1}$

Radiation field measurement around BigRIPS with a uranium beam

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To investigate the neutron field around BigRIPS, activation reaction rates of C, Al, Au and Bi samples were measured with a 345-MeV/u $^{238}U^{86+}$ beam in November, 2008. Effective doses due to neutrons and photons were also measured with thermoluminescence dosimeters (TLDs), of which the neutron dosimeter was developed by us. The beam was stopped at the BigRIPS beam dump and maximum intensity was about 0.35 pnA. The positions of samples and dosimeters are shown in Fig. 1. The circled numbers 1-9 are numbers of activation samples, and the letters A-G enclosed in squares indicate TLD dosimeters.

The induced radioactivity of samples was measured with Ge detectors, and the reaction rate, y (U^{-1} [sample atom]$^{-1}$), was obtained with the following formula.

$$ y = N_T \times 86 \times 1.602 \times 10^{-19} \Big/ \left(N_S \int_o^T q(t) \times e^{-\lambda(T-t)} dt \right) $$

Where N_T is the number of radionuclides at the end of irradiation, N_S is the number of atoms in the sample, T is the irradiation length, $q(t)$ is the U beam current in amperes at time, t, and λ is the decay constant.

The results for the reaction rate, y, are shown in Table 1. Threshold reactions at positions 3 and 4 were below the detection limit, and the $^{197}Au(n,\gamma)^{198}Au$ reaction rates were found to be only 1.1×10^{-29} and 2.0×10^{-28} for positions 3 and 4, respectively. Any activity at position 9 was not observed.

The dose equivalents measured with TLD dosimeters are shown in Table 2. Background radiation is not included in these values. It is difficult to estimate the error in these values, but it seems to be more than several tens of % in the results for position B and the photon result for position E.
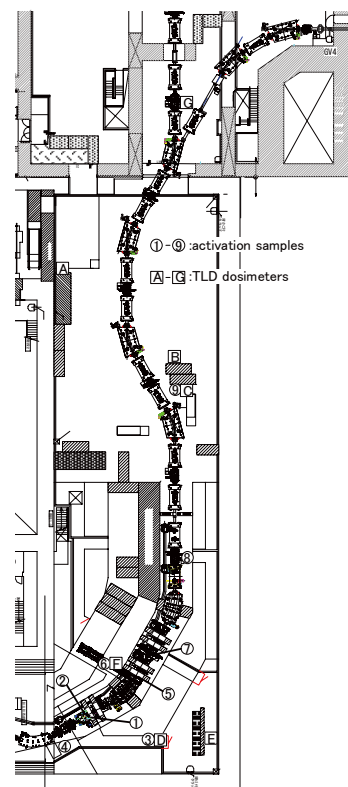
Fig. 1. Positions of samples and dosimeters around BigRIPS.

Table 1. Measured reaction rates per one $^{238}U^{86+}$ ion per one atom of activation sample.

type of reaction	half life	E_{th} (MeV)	position 1	2	5	6	7	8
$^{12}C(n,2n\alpha)^7Be$	53.1d	28.5	6.5e-30[1)]	8.5e-32[2)]	8.3e-30	-[3)]	-	-
$^{12}C(n,2n)^{11}C$	20.3m	20.3	1.7e-29	1.6e-31	1.8e-29	-	2.0e-32	-
$^{27}Al(n,\alpha)^{24}Na$	15.0h	3.2	1.1e-29	4.0e-31	1.9e-29	-	1.4e-32	3.3e-33
$^{197}Au(n,\gamma)^{198}Au$	2.69d		2.5e-27	2.2e-27	4.6e-27	5.5e-29	1.0e-27	7.3e-31
$^{197}Au(n,2n)^{196}Au$	6.18d	8.1	2.5e-28	1.1e-29	3.5e-28	-	-	-
$^{197}Au(n,4n)^{194}Au$	1.64d	23.2	9.0e-29	2.5e-30	1.3e-28	-	-	-
$^{209}Bi(n,4n)^{206}Bi$	6.24d	22.6	1.2e-28	2.9e-30	1.1e-28	9.2e-33	1.6e-31	2.0e-32
$^{209}Bi(n,5n)^{205}Bi$	15.3d	29.6	1.4e-28	2.6e-30	1.3e-28	1.1e-32	1.9e-31	2.2e-32
$^{209}Bi(n,6n)^{204}Bi$	11.2h	38.1	7.0e-29	6.8e-31	5.3e-29	-	5.2e-32	2.0e-32
$^{209}Bi(n,7n)^{203}Bi$	11.8h	45.4	7.4e-29	5.2e-31	4.0e-29	-	6.8e-32	1.3e-32
$^{209}Bi(n,8n)^{202}Bi$	1.72h	54.2	7.5e-29	3.3e-31	4.7e-29	-	9.3e-32	1.3e-32
$^{209}Bi(n,9n)^{201}Bi$	1.80h	61.7	3.2e-29	1.9e-31	2.7e-29	-	-	-
$^{209}Bi(n,10n)^{200}Bi$	36.4m	70.9	3.0e-29	-	2.3e-29	-	-	-

1) Read as 6.5×10^{-30}.   2) Underline indicates error larger than 10%.   3) Lower than detection limit.

Table 2. Dose equivalent rate (μSv/h) at 1-pnA $^{238}U^{86+}$ ion beam measured with TLD dosimeters.

type of radiation	position A	B	C	D	E	F	G
neutron	-[1)]	0.080	11	260	1.4	2500	3.8
photon	-	0.56	1.4	30	0.32	160	-

1) Lower than detection limit.

*1 Japan Environment Research Corp.

Operation of Cryogenic System for the Superconducting Ring Cyclotron

H. Okuno, T. Dantsuka, K. Yamada, M. Kase, O. Kamigaito and Y. Yano

2008 was a tough year for operation of the superconducting ring cyclotron (SRC) cryogenic system. Oil contamination of the helium refrigerator from the compressor forced us to stop operation for six months in order to clean up the oil-contaminated He refrigerator and to install two additional oil separators to the existing helium compressor units. A few drops of oil found at the seats of the low temperature valves in the helium refrigerator alerted us of the oil contamination in February. Further investigation of the inside of the refrigerator showed the contamination to be very severe and dispersed over the whole refrigerator. We decided that internal parts (pipes, heat exchangers etc.) should be cleaned with florine225 to remove the oil in the helium refrigerator. Clean-up of the heat exchangers in particular was very tough work. We took them to the clean factory to allow them to wash them in the various angles. Another important task was to increase oil separation capability by adding 2-stage oil separators. Details of the restoration are described in the report by Dantsuka [1].

Restoration of the cryogenic system lasted until the end of August and Saitama prefecture allowed us to produce high pressure helium gas after the test according to the high pressure gas safety regulation on August 28, 2008. We restarted the helium compressor in order to check performances of the oil separation systems where the 2-stage separators were newly installed. Measured data showed that oil contamination was lower than the level which the cold trap monitor can detect (40 ppb) while designed contamination is 20 ppb. Next, we performed stand-alone operation to check cooling capacity. Some filters were installed to block incoming oil impurities. Pressure drops may be
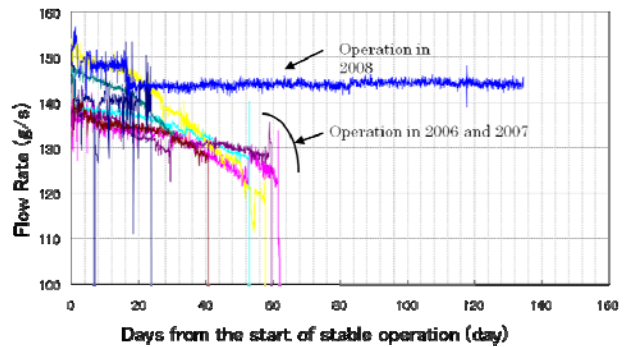
Fig. 2: Flow rate trends in the helium refrigerator.

generated at the filters, causing degradation of cooling power of the helium refrigerator. Measured cooling power was larger than that required for cooling of the SRC superconducting magnets. The two test results mentioned above let us proceed to the next stage of operation of the helium refrigerator in the connection with the superconducting magnets. After purification operation for about 1 week, we started cool-down operation of the superconducting magnets. Fig. 1 shows the cool-down curves with those obtained in the operation of 2005. It took about 22 days to cool-down the superconducting magnets from room temperature to 4.2 K, indicating no degradation of cooling power compared with first cool-down when the refrigerator contained no oil. After the end of cool-down operation, liquid helium was transferred to the
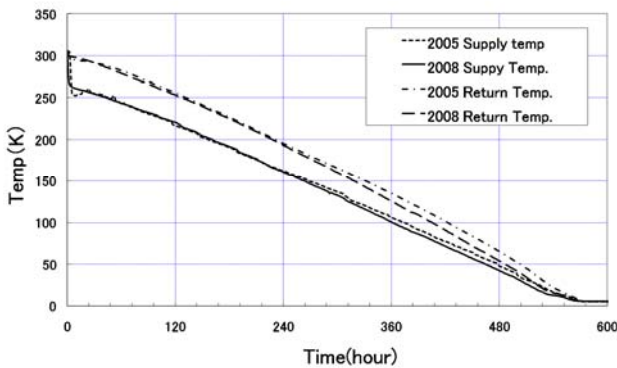
Fig. 1: Cool-down curves of the SRC superconducting magnets.
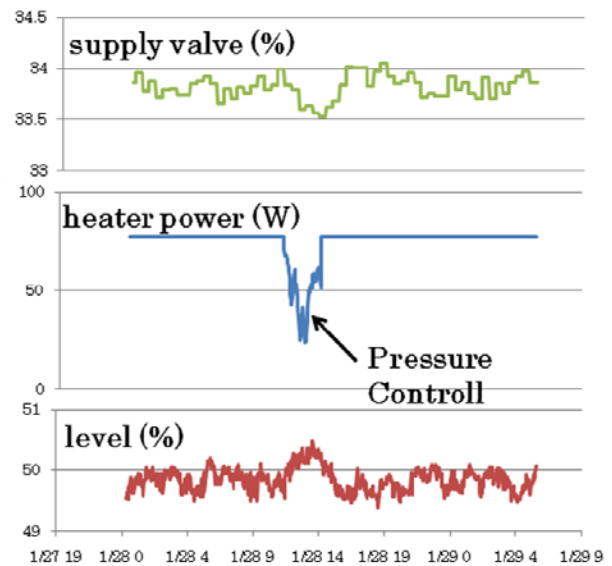
Fig. 3: Performance of the control of the liquid helium level.
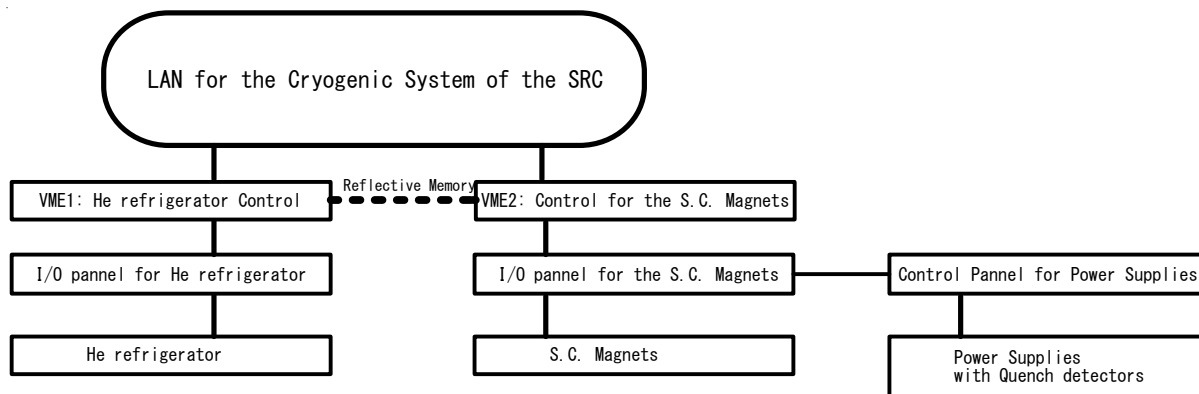
Fig. 4: Cryogenic control system for the SRC superconducting magnets and helium refrigerator.

helium vessel for the magnets and steady operation was attained on October 3, 2008. The superconducting magnets were excited to accelerate uranium and calcium beams in the SRC in November and December of 2008. At present (February 2009) stable steady operation is continuing without any severe trouble requiring us to stop the refrigerators. Fig. 2 shows the flow rate trend through the helium refrigerator with the trends during 2006-2007 operation. Long-term operation lasted more than 100 days, showing no sign of degradation of the flow rate, while operation in 2006 and 2007 was terminated around 60 days due to degradation. These trend graphs clearly suggest that this phenomenon occurred due to oil contamination in the refrigerators and the present refrigerator was very clean. In 2006-2007 we warmed up the refrigerator every two months to room temperature to recover cooling power. We understand now that the frequent warm-ups made the oil to disperse to all the pipes of the refrigerator.

In stable operation the thermal load to the superconducting magnets is almost constant. Slow feedback is enough to maintain the level of the liquid helium in the 2000 L reserve tank. The ratio of supply valve opening in the refrigerator to the magnet is automatically changed by the magnitude of -0.6 x (level change) every 30 minutes. Fig. 3 shows good performance of the level control. A large change in the heat load occurs in excitation and de-excitation of the

superconducting magnets due to eddy current in the aluminum support for the superconducting trim coils. This change in the heat load can be compensated by changing the power of the heater in the helium vessel, thereby keeping pressure constant in the vessel. Fig. 4 shows that this pressure control moderates disturbances in the liquid level and temperature distribution inside the helium refrigerators. An interlock and alarm system were installed for safety of long-term operation. The figure shows the cryogenic control system of the helium refrigerator and superconducting magnets. The system consists of VME1 for control of the refrigerator and VME2 for control of the cryogenic parts of superconducting magnets. Each VME has a reflective shared memory connected with the other through optical fibers. This system can communicate with the power supply control panel where important information on the superconducting magnets is gathered. Table 1 lists conditions and actions of the interlocks which prevent serious trouble involving the magnets and the refrigerator. Monitoring oil contamination from the compressor is very important for preventing oil contamination of the helium refrigerator again. Cold trap measurement after the final stage is performed once every two months and oil contamination after each separator was measured once a month. Oil volume in the drain of the each separator is continuously monitored. Operation will continue until the end of the next June to check that oil separation system works well even after a 9 month period of long term operation.

Action	Condition
Fast shut down & isolation of the He refrigerator	Quench. Bad thermal insulating vacuum.
Slow shut down	Compressor or Turbine Trip. High or low liquid He level. High temp. of the S.C. coils. Low flow of gas He to P.L. High temp. of P.L. Low flow of the liquid He to the S.C. trim and SBM.

Table 1: Interlock list for the SRC superconducting magnets.

Reference
1). T. Dantsuka, et. al. in this report.

Oil contamination of the cryogenic system for SRC

T. Dantsuka, H. Okuno and M. Kase

Operation of the He refrigerator for SRC was stopped in 2008 due to oil from the compressor contaminating the refrigerator. It took six months to investigate and recover from the problem. Subsequent operation started in September, and has been very stable thanks to a complete recovery process [1]. This report describes details of the investigation and recovery.

The cryogenic system for SRC started operation in the autumn of 2005. The system successfully cooled-down the large superconducting magnets for SRC to carry out magnetic field measurements and beam commissioning from 2006 to 2007. However operation of the refrigerator itself was not very satisfactory, and it had to be stopped every two months due to degradation of cooling power. Investigation of impurities such as H_2O and N_2 was carried out during operation, but did not suggest any reason why the cooling capacity degrades in such short period of two months. The cryogenic system for BigRIPS also had a similar problem. In February of 2008, however, a few drops of oil were found at the seat of the cryogenic valves in the He refrigerator for BigRIPS, and this gave us the key to solve the problem. The next day oil was also found in the SRC refrigerator, and investigation of the oil contamination was initiated.

First, we focused on the investigating how much oil is contained in the He refrigerator and where the oil

vacuum pump and so on. We opened the filter located just upstream of the first turbine as shown in Fig. 1 to check whether oil reached there by going through the 80K adsorber made from charcoal which protects against oil from the compressor. We found a mixture of the charcoal and oil there, strongly indicating that oil coming from the compressor is enough to overload 80K adsorber and the lower temperature stage of the He refrigerator. Next the 1st heat exchanger (HX) was inspected. Alarge amount of oil was found there, and it was very difficult to remove the oil with AK225 cleaner (HCFC-225ca) from the HXs because it has a complicated structure and sits in sideways. Less than ten percent of the oil contained in the 1st HX could be removed after much trial and error. So we decided cut the units of the 1st – 4th HXs from the refrigerator in April for cleaning in the factory, which would allow us to clean them in various sitting angles and access the lower temperature region of the He refrigerator. Fig. 2 shows the cleaning process for each heat exchanger unit in the factory. Cleaning enables us to know the correct volume of contamination of the oil and charcoal from the 80K adsorber. Inspection of the lower temperature region at the RIKEN site gave us the volume of the oil using NVR (Non Volatile Residue) technique. Finally it was found that about 400 cc of oil was contained in the helium refrigerator
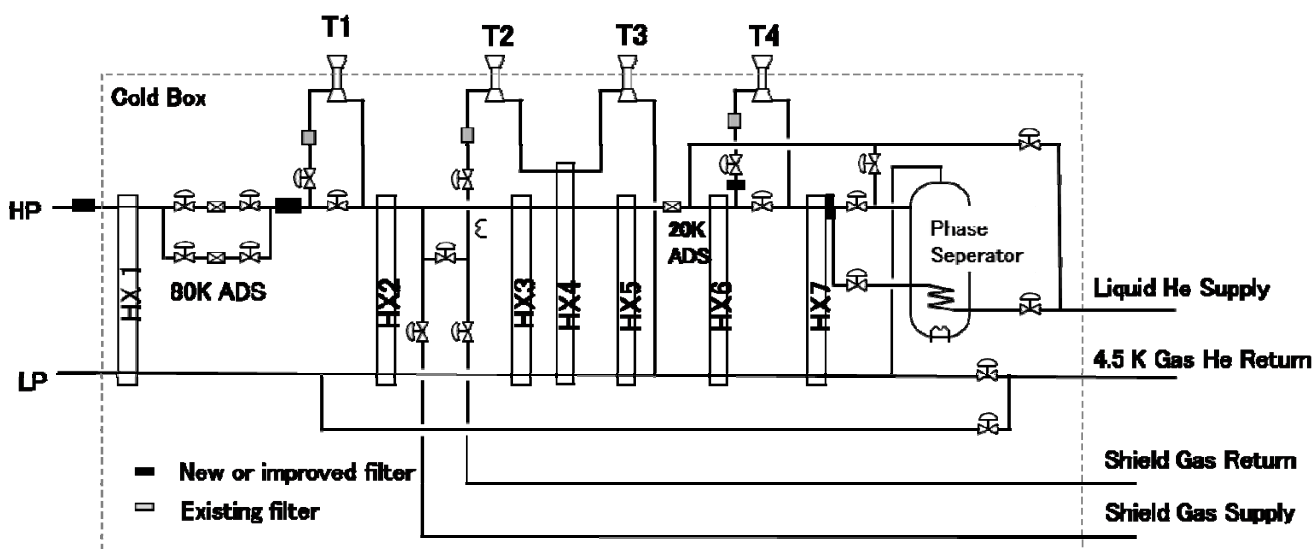
Fig. 1. Diagram of the SRC He refrigerator. T1-T4 stand for the first – fourth turbines, and HX1-7 stand for the 1st-7th heat exchangers. The new or improved filters are shown with the existing filters.

comes from. Infrared spectroscopy of the oil made it clear that it came from the screw compressor not the

and cleaning was carried out to reduce the contained oil up to about 4 cc. Replacement of charcoal in the 80

Fig. 2. Cleaning process of the heat exchangers in the factory.

Fig. 3. Oil separators for the He compressors. The 1.5[th] and 5th separators were newly installed.

K adsorber was a hard task due to the limited access to the inside. Filling charcoal into the vessel for the 80 K adsorber without spaces is important to prevent degradation of the charcoal, which can damage the seats of the cryogenic valves and the heat exchangers in the He refrigerators. This was successfully done after much try and error.

In parallel with the cleaning process, additional oil separators were designed after reconsidering the oil separation system in the compressor unit. Originally it consisted of four oil separators. The 1st is the demister type, the 2 and 3rd consist of coalescer elements and the 4th consists of charcoal and molecular sieves. We decided to add a coalescer element (the 1.5th separator) and a 5th separator made of charcoal as shown in Fig. 3. Estimated oil contamination is about 10 ppb which is smaller than the original design values by 10 ppb. Furthermore, filters to prevent incoming oil were installed before and in the inside of the helium refrigerator as shown in the Fig. 1. The recovery process, including many welding points for the pipe and covering super insulators, was the next important issue. Welding was an especially hard task in the limited space inside the refrigerator.

Permission to make the high pressure gas was given on Aug. 28, 2008 by Saitama Prefecture after the entire recovery process was complete. Tests of compressor running and stand-alone operation of the refrigerator were performed before we started to cool-down the superconducting magnets for SRC. The test results showed that cooling power in stand-alone operation was 1378.2 W at 4.5 K while initial cooling power was 1410.4 W in 2004. This degradation, which is allowable for cool-down of the SRC magnets, may arise from pressure drops caused by adding some filters to the high pressure lines of the refrigerators.
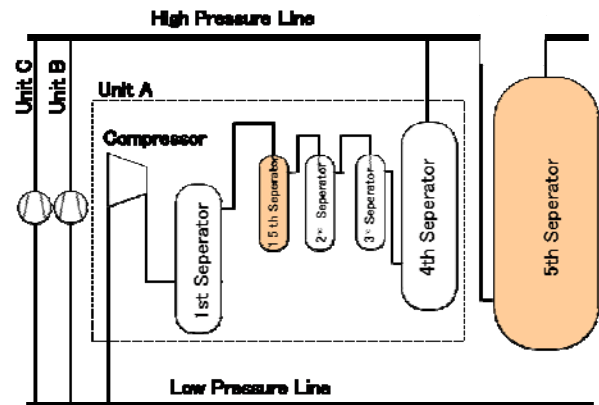
The process for cleaning and recovery gave us the opportunity to inspect the inside of the refrigerator, even though the main purpose was to remove oil from the refrigerator. First we found a large amount of metallic dust in the phase separator. We found that this dust comes from factory processes and left it untouched because the probability of it affecting the turbines and superconducting coils is thought to be very low. Second, we found a leak in the heat exchanger made of copper pipe placed in the phase separator. This unit improves the quality of the liquid helium before supplying it to the magnet. This leak is allowable for the present operation but we are afraid that it will become larger in long term operation, resulting in pressure in the pipe becoming the same as that in the phase separators, and causing the supply of liquid helium to stop. We will keep monitoring the leak by checking again after one year of operation.

References
1) H. Okuno et. al.: in this report.

Present status of the BigRIPS cryogenic plant

K. Kusaka, M. Ohtake, T. Kubo, K. Yoshida, A. Yoshida, T. Ohnishi, Y. Yanagisawa, N. Fukuda, Y. Yano,

M. Nobutoki,[*1] H. Ito,[*2] T. Sasaki,[*2] N. Kakutani,[*2] T. Tsuchihasi,[*2] and K. Sato[*2]

The five superconducting triplet quadrupoles (STQ1 – STQ5) in the first stage of the BigRIPS separator are cooled by a large liquid helium cryogenic plant. The main components are a Linde-TCF50S refrigerator (cold box), a Mayekawa 315 kW compressor unit, one 10 m³ and two 100 m³ helium buffer tanks, a 2000 L liquid helium Dewar vessel, and a 50-m-long transfer line.[1] The whole cryogenic system, including the STQs was fabricated by Toshiba Corporation and Taiyo Nippon Sanso Corporation, and installed in the RIBF building at the beginning of 2004.

Test operation of the BigRIPS cryogenic plant was performed from March 2004 to June 2006.[2,3] Stand-alone tests of the cold box and heat-load measurements of the transfer line were conducted untill August 2005. The first cooling operation of the whole system was performed in October and November 2004 and took 20 days.[2] The measurement results and the estimated excess cooling capacity are summarized in ref. 2 and ref. 3. The second cooling operation was performed in May and June 2006. Excitation tests of the STQs, and the simultaneous excitation of all the BigRIPS magnets were successfully performed during 43 days of continuous operation in the refrigerator mode.[3]

Regular operation of the BigRIPS cryogenic plant started in October 2006. The cryogenic plant typically operates according to the following thermal cycle: purification of helium gas, pre-cooling, liquefaction, steady state operation in refrigerator mode, and warm-up.

The first operation cycle was from October 2006 to January 2007 (Cycle I). After 3 weeks of steady operation in the refrigerator mode, the heater power in the phase separator (PS), which corresponds to the excess of cooling capacity, started decreasing gradually. We stopped the refrigerator after 53 days of operation in the refrigerator mode, since we could not keep the liquid helium levels in the cryostats of STQs constant. We then warmed up the cold box separately and re-cooled the whole system after purification operation while taking great care regarding impurity concentration in the helium gas.[3]

The second cycle was from January to April 2007 (Cycle II) in which the first RI beam has been successfully produced by the BigRIPS separator. However, we were again forced to stop the refrigerator after 59 days of steady state operation due to degradation of the cooling capacity.

We repeated two more thermal cycles prior to July 2007 in the same way as Cycle I and II in accordance with the BigRIPS beam time schedule. The third cycle (Cycle III) was from April to June 2007 and the fourth (Cycle IV) was

from June to July 2007. Commissioning experiments of BigRIPS separator were successfully performed in these periods. The cooling capacity decreased gradually in both cycles. The periods of steady operation in refrigerator mode were 39 days and 43 days in Cycle III and Cycle IV, respectively. As reported in ref. 3, we have measured the inorganic impurity concentrations in helium gas repeatedly in these cycles, but we could not find the reason for the cooling-capacity deterioration.

After a series of these operation cycles, we conducted maintenance on the oil-removal module of the compressor unit and some of the cryogenic valves in the cold box in early 2008. In February 2008 when the cryogenic valve at the entrance of the 80K adsorber (ADS) which leaked in Cycle IV was removed for maintenance, a small amount of oil was found on the valve sheet. The oil contamination in the cold box was investigated using fiber scopes and it was found that the heat exchangers and internal high pressure lines in the cold box were contaminated. The high pressure line between the compressor unit and the cold box was also investigated and oil was found in the strainer at the entrance of the cold box. The oil was identified by Fourier transform infrared (FTIR) spectroscopy analysis as coming from the compressor unit. We have concluded that the reason for the decreasing cooling capacity oil contamination in the heat exchangers.

The oil removal module of the compressor unit was then investigated using the oil check kit which is often used by the compressor manufacturer. The oil contamination level is measured by the size of oil spots on a prepared slide on which sampling helium gas was blown. Our main compressor is a 2-stage oil-flooded screw type with a flow rate of 73.5 g/sec and a discharge pressure of 1.60 MPaG. Compressor lubricant injected to the screws is separated from the discharged helium gas using a 4-stage oil removal module comprised of an oil vessel with a demister as a bulk oil separator, two coalescer vessels, and an adsorbent vessel which contains activated charcoal and molecular sieves. Residual oil at the exit of each separator stage was measured to be 3750, 100, 7.5, and 1.25 ppm (weight) in 2008, whereas it was 2500, 5, <0.25, and < 0.25 ppm (weight) in 2004. FTIR combined with the cold trap method was also performed in 2004 to measure oil contamination at the exit of the adsorbent vessel and the result was less than 40 ppb (weight). Since residual oil at the exit of the adsorbent vessel was too high, we decided not to perform cold trap measurement in 2008. The significant increase in oil contamination at the exits of the two coalescer vessels suggests an unusual change of the coalescer filters during long term operation, so we opened

*1 Taiyo Nippon Sanso Corporation
*2 Toshiba Corporation

the two coalescer vessels and investigated the coalescer filter elements and their seal rings. However, we could not find anything unusual in the coalescer vessels. Although we could not find a clear cause of the oil carry over, we came to the conclusion that the oil removal module must be improved.

We have decided to build an additional charcoal vessel and extra coalescer vessel in order to improve the performance of the oil removal module. The design of the new compressor unit is schematically shown in Fig. 1. The newly introduced third coalescer vessel is identical with the original two coalescer vessels and the design of the final charcoal vessel is based on the oil-removal unit in the RIKEN-RAL Muon facility. We expect the oil contamination to be 0.008-0.02 ppm after the improvement. We have also installed solenoid valves in the oil return lines to control the oil level in the coalescer vessels. By counting the valve actions we can estimate the oil separation performance of the coalescer filters.
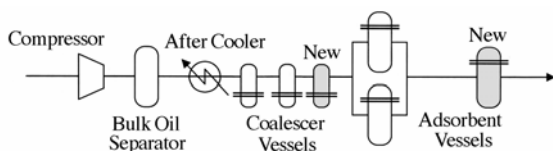
Fig. 1. Schematic diagram of the improved compressor unit.

While the additional charcoal vessel and coalescer vessel were being fabricated, we cleaned the cold box and the high pressure lines using the solvent HCFC225cb. In April 2008, the cold box was shipped to the factory where the transfer line was fabricated and all the heat exchangers were cleaned by cutting internal pipes and filling HCFC225cb. The filling solvent was drained and the amount of oil was evaluated using the non-volatile residue (NVR) method. We have repeated this process 9 to 11 times for each heat exchanger. Most of the pipes in the cold box except those in low pressure lines and the PS were also cleaned in the same manner. The total amount of remaining oil after cleaning was evaluated to be 0.34 mg (0.42 cc) using the NVR test. The remaining solvent HCFC25cb in the cleaned parts was then evaporated by sending warm N_2 gas. We confirmed whether the solvent HCFC25cb and water were dried from the cleaned parts by measuring HCFC25cb concentration in the outlet N_2 gas using the gas detector tubes and a dew point meter. All the parts were dried until HCFC25cb concentrations were less than the sensibility of the detector tube (1.4 ppm) and the dew point was in the range between -60.8 and -84.1 degree. The contaminated 80K- and 20K-ADSs and inlet filter of the turbine were replaced with improved new ones in which adsorbent charcoal was tightly filled. The cryogenic valves were disassembled and wiped to clean off possible oil contamination and the valve sheets were replaced with new ones.

Cleaning of the cold box took about 2.5 months and reassembly of the cold box at the factory was finished at the end of July 2008. Then the cold box was shipped to

RIKEN. The pipes of the high pressure lines from the compressor unit to the cold box were also cleaned by filling with HCFC225cb in early July. The new coalescer vessel and charcoal vessel were fabricated and shipped to RIKEN in mid July and installation was finished at the end of July. Reassembly of the whole system was finished in mid August and the series of test operations was finished in early September.

Stand alone operation of the cold box and cooling capacity measurement have been performed. After optimizing operation parameters such as temperature of helium gas at the entrance and exit of expansion turbines, the maximum cooling capacity was measured to be 496 W at 4.5 K at PS and 833 W at 80 K lines with a pressure of 1.35 MPaG at the entrance of the first expansion turbine T1. Converting the 80 K cooling capacity to the one at 4.5 K, the total cooling capacity is evaluated to be 543.1 W. Temperature of the discharge gas from the compressor unit, which depends on the temperature of cooling water was 32.7 degrees. Taking into account the discharge gas temperature dependence, the total cooling capacity of 543.1 W corresponds to 563.7 W with the discharge gas at 19.0 degrees, which is consistent with the result obtained in 2004 (560.5 W).[2,3]

Continuous operation of the BigRIPS cryogenic plant started on September 11, 2008. After one week of purification operation, STQ1 - STQ5 were cooled from room temperature to 4 K in 18 days, and it took another 3 days to fill the cryostats with liquid helium. Steady state operation in refrigerator mode started on October 7 and we are planning to maintain continuous operation until June 2009. Figure 2 shows the flow rate of turbine T1 in the steady-operation period up to the end of January 2009 together with the flow rate for Cycle I-IV. After fixing the operation parameters on 70-th day in the refrigerator mode, the T1 flow rate has stayed almost constant, so that we have confirmed that improved oil removal module works well.

Performance of the oil removal module in the compressor unit has been checked by the cold trap method, and oil contamination at the exit of the compressor unit has been measured to be better than 10 ppb so far. Details on oil concentration measurement at each stage of oil separators will be reported in the near future.
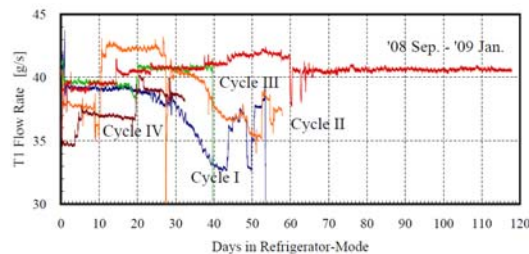
Fig. 2. T1 flow rates as functions of the operation period in refrigerator mode.

References
1) T. Kubo et al.: RIKEN Accel. Prog. Rep. **36**, 316 (2003).
2) T. Kubo et al.: RIKEN Accel. Prog. Rep. **38**, 289 (2005).
3) K. Kusaka et al.: RIKEN Accel. Prog. Rep. **41**, 244 (2008).

Present status of liquid-helium supply and recovery system

K. Ikegami, H. Okuno, M. Nakamura, T. Maie, T. Dan s t uka, and M. Kase

A liquid-helium supply and recovery system,[1] which can generate liquid helium at a rate of 200 L/h from pure helium gas, has been stably operating since the beginning of April 2001. The volumes of liquid helium supplied per year are listed in Table 1. The supplied volume has gradually increased from 2006 to 2007. The volume supplied to the low temperature physics laboratory in 2007 increased more than 10 kiloliter over 2006. The exploratory materials team in the category "other laboratories" began to use liquid-helium for the first time in March 2008. The laboratory for human brain dynamics in the brain science institute finished using liquid-helium at the end of September 2008.

The control system of the compressor for liquefying helium gas was tripped several times at the end of August and in the middle of November 2008 after the electricity stoppage plan. The cause of the trips is unknown and is now under examination.

A new recovery pipe was connected from the south side of the laser science laboratory to the recovery station behind the BSI east brain building at the end of October.

The purity of helium gas recovered from laboratories improved gradually after the completion of the system. The volume of recovered helium gas sent from each building on the Wako campus to the liquid-helium supply and recovery system has been measured. The recovery efficiency, defined as the ratio of the recovered helium gas to supplied liquid helium has been measured. Recovery efficiency for the south side of the Wako campus - such as the cooperation center building for the advanced device laboratory, the chemistry and material physics building, and nanoscience joint laboratory building - became more than 90%. Recovery efficiencies of the main research building and the laser science laboratory are very low. Average recovery efficiency measured from December 2005 to March 2008 is shown in Fig.1. Average recovery efficiency for two years has risen above 85%.
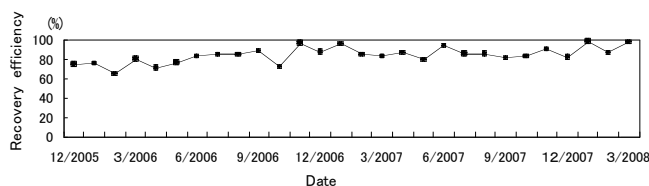
Fig. 1 Average recovery efficiency measured from December 2005 to March 2008.

At the end of April 2008, a hydrogen removal apparatus[2] which has a weight of 1.7kg of the silver-zeolite "Ag-400" was installed in the system to adsorb hydrogen gas in recovery gases. The helium gas circulated in the system is returned to the gas bag of the system through the hydrogen removal apparatus without ejection in to the air. We expect that volume of purchased helium gas will decrease. Fig 2 is a diagram of the system installed in the hydrogen removal apparatus.

Reference s
1) K. Ikegami et al.: RIKEN Accel. Prog. Rep. **34**, 349 (2001).
2) M. Nakamura et al.: RIKEN Accel. Prog. Rep. **41**, 111 (2007).

Year	2001	2002	2003	2004	2005	2006	2007
Laboratory & institute	Amount of supplied liquid helium (ℓ)						
Magnetic materials laboratory	3392	7024	7713	11829	15672	16512	23282
Low-temperature physics laboratory	1270	3090	6966	9515	34713	29520	39855
Advanced device laboratory	9977	10849	9726	7401	11264	15017	14733
Condensed molecular materials laboratory	1939	1615	3079	5353	5912	7772	5331
Surface chemistry laboratory	1146	1676	4533	5007	5370	5486	3636
Brain science institute	6277	8144	5055	6292	7285	6956	6480
Other laboratories	3535	7730	14476	9487	15717	14767	15877
Total	27536	40182	51530	54884	95933	96030	109194

Table 1. Volumes of liquid helium supplied to laboratories per year from 2001 to 2007

Buffer Tank

Gas Cadres(Pure)

Liquid Nitrogen Tank

T1 and T2 : Turbines

T1 TI313 T2 TI3151

to atmoshere

PV3021B

CV3615

CV3165 CV3175

PV3108
77K

CV3130

Compressor

GS002 PV3022

CV3170

PV3021A

CV3229 PV3122

CV3269

CV3290

75Nm3 x 12

75Nm3 x 24

MV4021

PV3410

75Nm3 x 24

to Gas Bag

Heat exc.

Gas Cadres(Impure)

CV3401

Hydorgen
Removal
Apparatus

CV3420

CV3430

CV3415

CV3435 Vaccum

Liquid Helium Vessel

to Atmosphere

Fig. 2   Diagram of system installed in the hydrogen removal apparatus.

V. RECORDS OF LABORATORIES, GROUPS, AND TEAMS
(Activities and Members)

Events of Nishina Center & CNS from Jan. 2008 to Mar. 2009

2008

18, Jan.	Tree Planting Ceremony of "Nishina Zao"
30, Jan.	Conclusion of the Agreemenet "French-Japanese International Associated Laboratory for Nuclear Structure Problems" at CNRS, Paris
18-19, Feb.	The 3rd Program Advisory Committee meeting for Nuclear Physics (NP-PAC)
27-28, Mar.	The 4th Program Advisory Committee meeting for Materials and Life Science (MP-PAC)
19, Apr.	RIKEN Wako Institute Open Day
22, Apr.	RBRC Management and Steering Committee at BNL
Apr.	The SCRIT team demonstrated the base technology of Self-Confining RI Ion Target
2, May	A paper on development of SCRIT (Self-Confining RI Target) was issued in Phys. Rev. Lett.
3-4, May	Science School for High School Students "A Starry Sky Tour/Travel among Elements"
17, Jun.	Memorandum of Understanding (MOU) between Nishina Center and Indonesian Universities for Material Sciences using Muons at the RIKEN-RAL muon facility
25, Jul.	A paper on the discovery of new Pd isotopes, ^{125}Pa and ^{126}Pd, was published in JPSJ online
Summer	Maintenance and upgrade of the Liquid Helium Cryogenic Plants
26, Aug.-1, Sep.	The 7th CNS-EFES (International Research Network for Exotic Femto Systems) summer school was held
Sep.	The SLOWRI team performed the 1st laser cooling and precision spectroscopy
6, Oct.	CNS (Univ. of Tokyo)-RIKEN Collaborative Research Liaison Council (annual meeting)
6, Oct.	Lecture Commemorating 10th year of Collaborative Research on Heavy Ion Physics between the Univ. of Tokyo and RIKEN"
7-16, Oct.	Peking University "Nishina School"
4-5, Nov.	RIKEN-RAL Muon Facility International Advisory Committee
17-18, Nov.	RBRC Scientific Review Committee at BNL
20-21, Nov.	NP-PAC
22, Nov.	RIBF International User Group Meeting
Nov.	BigRIPS/Zero Degree Spectrometer (ZDS) Commissioning experiments
Nov.-Dec.	Commissioning of the Zero-degree Spectrometer
9-21, Dec.	Day One experiment in BigRIPS-ZeroDegree Spectrometer

2009

13-14, Jan.	ML-PAC
15-17, Jan.	Nishina Center Advisory Council (NCAC)
Dec.-Mar.	^{266}Bh production experiment
Mar.	SHARAQ (Spectroscopy of Hadronic Systems with Radioactive Qunyum Beam) Commissioning

Accelerator Division
Accelerator Development Group
Accelerator Team

1. Abstract

We are developing the key hardware in upgrading the RIBF accelerator complex. Firstly we are developing the challenging superconducting coils for the new 28 GHz ECR ion source which is being developed in order to increase the intensity of uranium beam. We are designing LEBT (Low Energy Beam Transport) which transport the high power beam from the ion source to the next injector linac. Correct estimations of neutralization of space charge forces are hard task. Finally we are developing long-lived charge stripper foils which are installed to breed the ion charges for reduction of their magnetic rigidities. We are also developing gas or windlow-less liquid lithium strippers.

2. Major Research Subjects

(1) Development of superconducting technology in acceleration system.
(2) Development of the LEBT (Low Energy Beam Transport) and the new injector for the high power beams.
(3) Development of charge strippers for high power beams (foil, gas, liquid)

3. Summary of Research Activity

(1) Development of superconducting technology in acceleration system.

Ohnishi, J., Okuno., H,

We are developing the challenging superconducting magnets for the 28GHz ECR ion source. We just started to study the possibility of the superconducting cavity in the RIBF accelerator complex.

(2) Development of the LEBT (Low Energy Beam Transport) and the new injector for the high power beams.

Sato, Y., Okuno, H.,

We are developing the LEBT for the ion beams from the new 28GHz ion source. We are also studying space charge effects in the new injector for the RIBF accelerator complex.

(3) Development of charge strippers for high power beams (foil, gas, liquid)

Hasebe, H., Kuboki, H., Yokouchi, S., Okuno, H.,

We are developing the long lived charge stripper for high power ion beams. Foils, gas and liquid for the strippers are being studied in parallel.

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Accelerator Division
Accelerator Development Group
Ion Source Team

1. Abstract
Our aim is to operate and develop the ECR ion sources for the accelerator-complex system of the RI Beam Factory. We focus on further upgrading the performance of the RI Beam Factory through the design and fabrication of a superconducting ECR heavy-ion source for production of high-intensity uranium ions.

2. Major Research Subjects

(1) Operation and development of the ECR ion sources

(2) Development of a superconducting ECR heavy-ion source for production of high-intensity uranium ions

3. Summary of Research Activity

(1) Operation and development of ECR ion sources

  T. Nakagawa, M. Kidera, Y. Higurashi, H. Haba, T. Kageyama and A. Goto

  We routinely produce and supply various kinds of heavy ions such as zinc and neon ions for the super-heavy element serach experiment as well as uranium ions for RIBF experiments. We also perform R&D's to meet the requirements for stable supply of high-intensity heavy ion beams.

(2) Development of a superconducting ECR ion source for use in production of a high-intensity uranium beam

  T. Nakagawa, J. Ohnishi, M. Kidera, Y. Higurashi, Y. Sato and A. Goto

  The RIBF is required to supply uranium beams with very high intensity so as to produce RI's. We have designed and are fabricating an ECR ion source with high magnetic field and high microwave-frequency, since the existing ECR ion sources have their limits in beam intensity. The coils of this ion source are designed to be superconducting for the production of high magnetic field. We are also designing the low-energy beam transport line of the superconducting ECR ion source.

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Accelerator Division
Accelerator Operation Group
RILAC Team

1. Abstract

The operation and maintenance of the RIKEN Heavy-ion Linac (RILAC) have been carried out. There are the two modes, the standalone mode, in which the beam is delivered directly to the low-energy beam user in the RILAC, and the injection mode, in which the RILAC beam is injected to the RIKEN Ring Cyclotron (RRC). The RILAC is composed of two ion sources, the frequency-variable RFQ linac, six frequency-variable cavities, and six energy booster cavities (CSM). The maintenance of these devices is important to keep the log-term stability of RILAC beams.

2. Major Research Subjects

(1) The long term stability of the RILAC operation.
(2) Improvement of efficiency of the RILAC operation.

3. Summary of Research Activity

The RIKEN Heavy-ion Linac (RILAC) is a frequency-tunable linac. The RILAC is composed of two Heavy-ion ECR ion sources, RFQ linac, six main cavities, and six energy booster cavities. Thousands hours are spent in a year for delivering many kinds of heavy-ion beams to various experiments.

The RILAC has two operation modes: the stand-alone operation delivering low-energy beams directly to experiments and the injection mode operation supplying beams into the RIKEN Ring Cyclotron (RRC). In the first mode, the RILAC supplies very important beam to the nuclear physics experiment of "the research of super heavy elements". In the second mode, the RILAC plays very important role as upstream end of the RIBF accelerators.

The maintenance is very important in order to keep the high quality performance of the RILAC. Improvements are always carried out for the purpose of more efficient operation.

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Member
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Research Consultants
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Masatake HEMMI
Yoshitoshi MIYAZAWA

Accelerator Division
Accelerator Operation Group
Cyclotron Team

1. Abstract

Together with other teams of Nishina Center accelerator division, maintaining and improving the RIBF cyclotron complex. The accelerator provides high intensity heavy ions. Our mission is to have stable operation of cyclotrons for high power beam operation. Recently stabilization of the rf system is a key issue to provide 10 kW heavy ion beam. To analyze

2. Major Research Subjects

  (1) RF technology for Cyclotrons
  (2) Beam-RF correlation analysis
  (3) Operation of RIBF cyclotron complex.
  (4) Maintenance and improvement of RIBF cyclotrons.

3. Summary of Research Activity

Development of the rf system for a stable operation.
Improvement and maitainance of rf cavities, deflection devices, beam lines.
Intoroduction of precise monitoring system.
Correlation analysis between rf and beam.

Team Leader
  Masayuki KASE

Members
  Naruhiko SAKAMOTO

Research Ascociate
  Kenji SUDA

Accelerator Division
Accelerator Operation Group
Beam Dynamics and Diagnostics Team

1. Abstract

In order to realize the efficient acceleration in RIBF accelerator complex, beam-dynamics studies based on realistic computer simulations and related technology (beam diagnosis, computer control, power supplies and charge stripper) were developed.

2. Major Research Subjects

(1) Improvement on the beam transmission along the multi-stage accelerator system.
(2) Development of beam diagnosis.
(3) Development of computer control.
(4) Improvement on long-term stabilities of power supplies and magnets.
(5) Development of charge stripper for high intensity heavy ion beam.

3. Summary of Research Activity

(1) Development of the beam diagnostic technology.
(2) Development of the charge-stripping foil.
(3) Development of the computer control system of accelerator.
(4) Investigation of beam behavior in accelerators.

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Accelerator Division
Accelerator Operation Group
Cryogenic Technology Team

1. Abstract

We are operating the cryogenic system for the superconducting ring cyclotron in RIBF. We are operating the helium cryogenic system in the south area of RIKEN Wako campus and delivering the liquid helium to users in RIKEN. We are trying to collect efficiently gas helium after usage of liquid helium.

2. Major Research Subjects

(1) The high efficiency of the liquid herium production cycle.
(2) Optimization of the large-scaled superconducting ring cyclotron.

3. Summary of Research Activity

We are operating the cryogenic system for the superconducting ring cyclotron in RIBF. Severe monitoring of the impurity is nessecary to realize that. We are operating the helium cryogenic system located in the south area of Wako campass of RIKEN. We are producing liquid helium and supplying them to RIKEN inside users. For the purpose of efficient operation, we are trying to collect the gas after the use of liquid helium.

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Nuclear Physics Research Division
Heavy Ion Nuclear Physics Laboratory

1. Abstract

   With fast RI beams provided by the RIBF cyclotron complex, we study exotic behavior of nuclei far from the stability valley, explosive nuclear burning in high-temperature and high-density environment in stars and early universe, and nuclear reactions related to solar neutrino production. For that purpose, we develop various experimental methods utilizing intermediate-energy inelastic scattering including Coulomb excitation, Coulomb dissociation, transfer- and fragmentation-reactions coupled with gamma- and particle-decay measurements. We perform also study of the three-nucleon forces by precise measurements of elastic scattering and breakup reactions of few-nucleon systems. New techniques including new laser-spectroscopy for exotic nuclei are also developed. Technical developments of radiation measurements such as semiconductor detectors and scintillation detectors, data processing methods, and construction of experimental equipment, together with theoretical studies on nuclear structure and nuclear reaction, are also made.

2. Major Research Subjects

   (1) Spectroscopy of unstable nuclei with direct reactions
   (2) Study of astrophysical nuclear reactions with fast beams of unstable nuclei
   (3) Three nucleon forces studied by intermediate-energy p+d scattering
   (4) Development of radiation detector systems with high performance
   (5) Development of laser spectroscopy for unstable nuclei
   (6) Theoretical studies on nuclear structure and nuclear reactions

3. Summary of Research Activity

3.1. Spectroscopy using direct reactions with gamma-ray measurements

   Proton inelastic scattering, Coulomb excitation, nucleon removal reactions on neutron- and proton-rich nuclei was studied by measuring gamma-rays in coincidence with the reaction products created in these reactions in inverse kinematics with fast RI beams. The evolution of shell structure, development of collectivity, and possible decoupling of proton- and neutron-motion are mainly studied.

(1) ^{32}Ne, ^{32}Mg, ^{34}Si−in island of inversion around N=20

   Proton inelastic scatterings on ^{32}Mg and ^{34}Si were studied. The experiment was aimed at clarifying the nature of the "islands of inversion" around N=20. The 4^+ state was identified for the first time and several new excited states were found in ^{32}Mg including a 3^- state, the location of which indicates disappearance of the sd-pf shell gap. The anomalously hindered B (E2) value for the 0^+-2^+ transition in ^{34}Si was compared with the neutron-transition multipole element extracted from the ^{34}Si (p, p') result. The very neutron rich nucleus ^{32}Ne was studied by the Coulomb excitation at the new facility of RIBF. The result indicates that this nucleus is in the island of inversion.

(2) ^{17,18}C−new method with transverse momentum measurement

   One neutron removal reaction with a hydrogen target was studied with ^{18}C and ^{19}C beams. The transverse momentum distributions, where the final states were identified by their gamma-decays, were analyzed, and their spins and parities were determined. The result indicates the usefulness of the transverse-momentum associated with proton induced nucleon removal processes for the spin-assignment with the help of new approach for the reaction process, *i. e.* CDCC.

(3) ^{62,64}Cr−behavior of neutron-rich nuclei around N=40

   Proton inelastic study with radioactive ^{62}Cr and ^{64}Cr beams has been performed at RIPS. Despite of the nature of magic nucleus observed in ^{68}Ni with neutron number N=40, development of static deformation was observed by the deformation length and the 4^+-2^+ ratio for ^{62}Cr and the location of the 2^+ state in ^{64}Cr.

(4) ^{20}Mg–role of four protons around the ^{16}O core

Coulomb excitation of the proton-rich nucleus ^{20}Mg was studied. Its B (E2) value for the 2^+ excitation was compared with that for the mirror nucleus ^{20}O. The large ratio between the neutron- and proton-matrix elements is consistent with the known core polarization effect induced by the valence nucleons, showing that the anomalous decoupling phenomena observed in ^{16}O is not observed in ^{20}O and ^{20}Mg.

3.2. Spectroscopy of unbound states using breakup and other reactions

(1) Invariant mass spectroscopy of nuclei in the vicinity of the neutron drip line

(a) Inelastic-scattering, one-neutron knockout, and charge exchange reactions of ^{14}Be were measured for proton and ^{12}C targets. The transition to the first 2^+ state of ^{14}Be at Ex=1.55 MeV was measured, which showed smaller deformation lengths compared to ^{12}Be. The invariant mass spectrum of ^{13}Be in the one-neutron knockout channel showed two peaks. The peak at higher energy around Ex=2 MeV has a d-wave property, and the lower one is of p-wave nature which indicates obliteration of he N=8 shell gap.

(b) Invariant mass spectra were obtained by the breakup and inelastic scattering of ^{6}He, ^{17}C, and ^{19}C on proton targets. New peaks were found for neutron-rich carbon isotopes.

(2) Invariant mass spectroscopy of proton-rich nuclei

Coulomb dissociation of the proton-rich nuclei ^{23}Al, ^{27}P, and ^{31}Cl on ^{208}Pb were measured. Relative energy spectra for ^{22}Mg+p, ^{26}Si+p, and ^{30}S+p were obtained. The breakup cross sections were converted to the radiative proton-capture cross sections, which provide useful information for the astrophysical network calculation on the explosive nucleosynthesis in novae and X-ray bursts.

(3) Missing mass spectroscopy of very neutron-rich light nuclei

Experimental search for the exotic ^{7}H system was performed in the d (^{8}He, ^{3}He) ^{7}H reaction using missing mass method. The excitation spectrum shows the peculiarity at ~ 2 MeV that can not be reproduced by a reasonable phase space distributions and might indicate the existence of the ^{7}H state at low excitation energy. Simultaneously, the strong peaks that corresponds to ^{7}He and ^{11}Li ground states were observed in the d (^{8}He, t) and d (^{12}Be, ^{3}He) reaction channels.

3.3. Experimental studies on the three nucleon forces

(1) Necessity of the three-nucleon-force is shown to reproduce the deuteron-proton elastic scattering cross section. To further investigate the three-nucleon-force, spin transfer coefficients for deuteron-proton breakup reactions were measured. Experiments at higher energies using the new RIBF accelerator complex are being prepared for the first measurement in 2009.

(2) Many experiments have been performed to test experimentally Bell's inequality. However, tests using hadron systems are limited. We tested Bell's inequality in the proton-neutron system by measuring the spin-correlation between the proton-neutron pair in $^{1}S_0$-state which was produced by the ^{2}H (*d, pn*) reaction.

3.4. "OROCHI" (Optical RI atom Observation in Condensed Helium as Ion-catcher) development

A novel nuclear laser spectroscopy technique for exotic nuclei trapped in superfluid helium, named as OROCHI (Optical RI-atom Observation in Condensed Helium as Ion-catcher), is being developed. We have carried out high precision measurement of Zeeman and hyperfine splittings of ^{85,87}Rb and ^{133}Cs atoms in superfluid helium, and successfully demonstrated that the nuclear spins and moments of unknown nuclei can be deduced by comparing their Zeeman and hyperfine splitting energies with those of known nuclei. We have also succeeded in optical pumping of non-alkali atoms such as Ag, which opens the door to the versatility of the OROCHI method. We are now ready to measure unknown spins and moments of exotic nuclei.

3.5. SCRIT development

We successfully finished feasibility studies of a novel experimental scheme, SCRIT (Self-Confining RI

Target), which makes it possible to study the internal structure of exotic nuclei by electron scattering. A prototype has been installed at the electron storage ring, KSR, of Kyoto University. We could measure electron scattering with Cs nucleus by the SCRIT scheme, and its principle has been verified. Construction of the system to be used in future experiments was started at RIBF.

3.6. SAMURAI

SAMURAI (Superconducting Analyzer for Multi-particle from Radio Isotope Beams) is a large-acceptance multi-particle spectrometer we will construct at RIBF. Its major part is of a large-gap superconducting magnet with 7 Tm of bending power. SAMURAI enables momentum analysis of heavy projectile fragments and projectile-rapidity protons with large angular and momentum acceptance. SAMURAI also affords projectile-rapidity neutron measurements with large angular acceptance in coincidence with heavy projectile fragments.

The construction budget has been approved, and is funded in four years from fiscal year 2008. The budget covers the superconducting dipole magnet and most part of detectors for heavy ions, neutrons, and protons. Our lab is, in particular, in charge of silicon strip detectors for protons and heavy ions and readout circuits requiring capability of broad dynamic range and high density signal processing. Our lab also partly takes care of the total arrangements of the SAMURAI collaboration group constituted by members from several institutes, each of which has unique physics interest.

Detailed design of the superconducting dipole magnet is to be finalized in fiscal year 2009. The magnet construction in RIBF will start early in 2010, and will complete early in 2011. The detectors are constructed in parallel. It is planned that the first SAMURAI experiment is performed in summer 2011.

3.7. Theoretical studies of nuclear physics

Most of the activities of theoretical nuclear physics have been moved to the Theoretical Nuclear Physics Laboratory led by T. Nakatsukasa.

Studies on nuclear structure at finite temperature are in progress: A self-consistent formulation of quasiparticle RPA including the effects of quantal and thermal fluctuations to study the properties of finite systems with pairing at finite temperature and angular momentum.

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Nuclear Physics Research Division
Radioactive Isotope Laboratory

1. Abstract

This laboratory explores exotic nuclear structures and dynamics in unstable nuclei that have never been investigated before, such as those with largely imbalanced proton and neutron numbers. Our aim is to develop new experimental techniques utilizing fast RI beams to discover new phenomena and properties in unstable nuclei. Another important subject is the equation-of-state of asymmetric nuclear matter, and its association with the origin of elements and with neutron stars. For instance, we are making attempts to the better understand underlyning mechanism for exotic stability-enhancements of very neutron-rich fluorine isotopes, the large deformation of the nucleus 34Mg with N=22 in spite of its vicinity to the N=20 magic neutron number and anomalous collectivity in 16C. We are further extending these studies to medium- and heavy-mass regions by developing facilities, detectors and unique methods at RIBF, thereby leading on the challenging task to find new exotic phenomena. We also perform numerical simulations of nucleosynthesis under the environment of core-collapse supernovae, and moreover quest for footprints of supernovae and solar activities in the past, embedded in Antarctic ice core, in collaboration with Cosmic radiation laboratory and National Institute of Polar Research.

2. Major Research Subjects

(1) Study of structure and dynamics of exotic nuclei through developments of new tools in terms of reaction- and technique-based methodology
(2) Research on EOS in asymmetric nuclear matter via heavy-ion induced reactions
(3) Promotion of nuclear astrophysics in an interdisciplinary organization
(4) Detector developments for spectroscopy and reaction studies

3. Summary of Research Activity

(1) Program based on missing mass method

Missing mass technique is promising for future radioactive isotope programs at RIBF. Detection of recoil particles from target is essential in excitation energy determination of particle unbound states without any assumption of particle- and gamma-decay processes, and also giving us transfer angular momentum from the angular distribution measurement. We have developed a solid hydrogen target as well as a detector system called ESPRI for proton- (in) elastic scattering. These systems have been employed for light mass nuclei available at the HIMAC facility. In addition, quasi-elastic scattering such as (p, 2p) reaction has been also performed with a (p2p) telescope at HIMAC. These programs are pilot programs for RIBF and being extended as RIBF programs. At low energies, spectroscopy on nuclei beyond the proton drip-line has been recently performed with MUST-2 at GANIL.

(2) Program based on in-beam gamma spectroscopy

In the medium and heavy mass region explored at RIBF, collective natures of nuclei are one of important subjects, which are obtained through production and observation of high excited and high spin states. To populate such states, heavy-ion induced reactions such as fragmentation, fission are useful and development of in-beam gamma methods fit for the reactions is necessary. So far, we have developed two-step fragmentation method as an efficient method to identify and populate excited states, and lifetime measurements to deduce transition strength.

(3) Decay spectroscopy

Beta- and isomer-spectroscopy is a traditional and efficient method for nuclear spectroscopy, especially for non-yrast levels. In the light mass region, several light-mass nuclei in both neutron-rich and proton-rich region have been investigated at RIPS through beta-gamma and beta-p coincidence technique. Concerning the medium and heavy mass region available at RIBF, we are developing two position-sensitive active-

stoppers to achieve low-background via position correlation; strip-silicon detectors and a cylindrical active stopper called CAITEN.

(4) Equation-of-state via heavy-ion central collisions

One of unsolved questions in projectile fragmentation at intermediate energies is target dependence of production cross sections for neutron-rich fragments. To seek for a possible mechanism we measured momentum distributions and cross sections of projectile fragments converted from a 90A MeV Ar-40 with Be and Ta targets. We found that differences between two targets are in production cross sections only. The cross section difference may stem from transfer/pick-up components or charge exchange ones. The similar measurements at the new facility could clarify which components are dominant. In addition, we observed in light mass fragments the acceleration phenomenon, which once had observed at GSI. These phenomena could give us an opportunity to study EOS of nuclear matter. Concerning RIBF programs, a detector for pions produced in heavy-ion collisions is being tested at the HIMAC.

(5) Interdisciplinary study for nuclear astrophysics

To understand the origin of elements beyond ion, interdisciplinary works are important in linking data from nuclear physics program. We are promoting simulation of nucleosynthesis in the r-process path, and investigation of Antarctic ice core to search for footprints of supernovae as well as solar activity in the past via mass spectrometer, to link data obtained from nuclear physics program.

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Nuclear Physics Research Division
Superheavy Element Laboratory

1. Abstract

The elements with their atomic number $Z > 103$ are called as trans-actinide or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Those elements are not exist in nature therefore, they must be produced by artificially for the scientific study of those elements. In our laboratory, we have been studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN and various methods of efficient production of the superheavy elements.

2. Major Research Subjects

(1) Search for new supreheavy elements
(2) Decay spectroscopy of the heaviest nuclei
(3) Study of the chemical properties of the heaviest elements
(4) Study of the reaction mechanism of the fusion process (theory)

3. Summary of Research Activity

(1) Searching for new elements

To expand the periodic table of elements and the nuclear chart, we will search for new elements.

(2) Spectroscopic study of the nucleus of heavy elements

Using the high sensitivity system for detecting the heaviest element, we plan to perform a spectroscopic study of nuclei of the heavy elements.

(3) Chemistry of superheavy elements

Study of chemistry of the trans-actinide (superheavy element) has just started world-wide, making it a new frontier in the field of chemistry. Relativistic effects in chemical property are predicted by many theoretical studies. We will try to develop this new field.

(4) Study of a reaction mechanism for fusion process

Superheavy elements have been produced by complete fusion reaction of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood theoretically. When we design an experiment to synthesize nuclei of the superheavy elements, we need to determine a beam-target combination and the most appropriate reaction energy. This is when the theory becomes important. We will try to develop a reaction theory useful in designing an experiment by collaborating with the theorists.

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Nuclear Physics Research Division
Theoretical Nuclear Physics Laboratory

1. Abstract

Nuclei are finite many-particle systems composed of protons and neutrons. They are self-bound in femto-scale (10^{-15}m) by the strong interaction (nuclear force) whose study was pioneered by Hideki Yukawa. Uncommon properties of the nuclear force (repulsive core, spin-isospin dependence, tensor force, etc.) prevent complete microscopic studies of nuclear structure. There exist number of unsolved problems even at present. In addition, radioactive beam facilities reveal novel aspects of unstable nuclei. We are tackling these old problems and new issues in theoretical nuclear physics, developing new models and pursuing large-scale calculations of quantum many-body systems. We are also strongly involved in research on other quantum many-body systems, to resolve mysteries in the quantum physics

2. Major Research Subjects

   (1) Nuclear structure and quantum reaction theories
   (2) First-principle calculations with the density functional theory for many Fermion systems
   (3) Computational nuclear physics

3. Summary of Research Activity

(1) Finite amplitude mothod for nuclear response calculations

   We have performed a systematic calculation of nuclear photoabsorption cross section for light nuclei. The calculation is fully self-consistent and is based on the time-dependent density-functional theory with the Skyrme functional. This is achieved using the finite amplitude method we have recently developed. The key feature of the method is to obtain the matrix elements of the random-phase approximation (RPA) in a simple way avoiding explicit calculation of induced residual fields. So far, even-even nuclei up to mass number A=80 have been studied.

   In addition, we have been working on extension of the finite amplitude method to nuclei where the pairing correlations are important. The basic equations have been derived and we are currently developing the computer program to calculate the linear response utilizing the finite amplitude method for the quasi-particle RPA.

(2) Large amplitude dynamics in shape coexistence phenomena

   Shape coexistence phenomena in proton-rich Se isotopes have been studied with the adiabatic self-consistent collective coordinate method. The canonical collective variables, mass parameter, and potential were determined self-consistently. The calculation indicates importance of the triaxial degrees of freedom for the tunneling dynamics between two quasi-vacua at prolate and oblate shapes. The collective Hamiltonian was requantized to calculate excitation spectra and transition properties for the first time. The shape mixing is hindered by coupling to the rotational motion to localize collective wave functions around prolate and oblate minima.

(3) Reaction cross section of stable and unstable nuclei

   We have studied the difference between the interaction cross section and the total reaction cross section for relativistic energies. We show that, for incident stable nuclei, the predicted difference is large enough to probe the nuclear structure, particularly in a mass region of less than around 40.

   We have systematically calculated the total reaction cross sections of oxygen isotopes, $^{15\text{-}24}$O, on a ^{12}C target at high energies using the Glauber theory. We have also studied the differential elastic-scattering cross sections of proton-^{20,21,23}O. The agreement between theoretical and experimental results is generally good, and our prediction for proton-^{20}O elastic scattering appears consistent with recent (preliminary) experimental data.

(4) Low-lying collective modes in deformed unstable nuclei

Low-frequency modes of excitation in deformed neutron-rich nuclei have been studied by means of the self-consistent Hartree-Fock-Bogoliubov and the quasiparticle-random-phase approximation based on the Skyrme energy density functional and the pairing density functional. We have investigated soft $K^\pi=0^+$ modes in neutron-rich Mg isotopes close to the drip line and have found that its strong collectivity is due to the coherent coupling between the beta vibration and the pairing vibration of neutrons.

(5) Density functional for description of novel pairing properties in nuclei far from stability

Our research focuses on the pairing properties in nucleonic systems under the extreme conditions; super neutron-rich nuclei ($N > 2Z$) and stellar interiors. We developed an energy density functional for pairing correlations (pair-DF) toward description of pairing properties in nuclei across the mass table. Our pair-DF is an indispensable ingredient for reliable prediction of the ground states and dynamical properties in super neutron-rich nuclei around heavy and medium-heavy mass regions, which are the main research targets in the RIKEN RIBF. We have completed the extensive calculation from (N-Z)/A=0 to 0.4 (neutron drip line region) for all even-even nuclei with N, Z > 40. From the analysis, we found the anomalous enhancement of pairing correlations in nuclei with large neutron excess, which can bring about various novel collective phenomena.

(6) Molecular structure of ^{12}Be studied with the generalized two-center cluster model

We have developed the generalized two-center cluster model (GTCM), which can handle the ionic, atomic, and covalent configurations in general two center systems. We have applied the GTCM to a unified study on structures and reactions in ^{12}Be. We have found that, above the alpha decay threshold, various chemical-bonding states coexist with a small energy interval. We also predicted that they were strongly populated through the two-neutron transfer reactions, alpha+^{8}He- > ^{6}He+^{6}He, which has been measured very recently at GANIL.

(7) Quantum condensed state of alpha particles in nuclei

We have investigated the quantum condensate state in nuclei, composed of a finite number of alpha particles, which are weakly interacting like a gas and condensed into the lowest mean field 0S orbit. We find a dilute density state in ^{16}O of strong alpha condensate character. The state is located at around the four-alpha breakup threshold as the sixth 0+ state. This discovery in this work is of a great significance in triggering further investigation in heavier nuclei.

(8) Many-body green's function approaches to nuclear structure

Numerical codes for Green's function theory were extended to achieve large-scale calculations using modern realistic nuclear interactions. Ab-initio studies of medium mass nuclei (up to A=60) are now being performed. Calculations for ^{56}Ni have reproduced the known spectroscopic factors. Based on this success, the dependence of nuclear correlations on proton-neutron asymmetry is being investigated. The quenching of experimental spectroscopic factors is currently an open puzzle for drip-line nuclei. Analogous calculations have been performed for electronic systems (atoms) to aid in developments of density functional theory.

(9) Smoothing method of S-matrix elements in CDCC calculations

One of the most reliable methods for treating the breakup processes is the method of continuum discretized coupled channels (CDCC). In CDCC, the calculated S-matrix elements are discrete in continuum, although the exact ones are continuous. Thus, one needs a smoothing procedure of the S-matrix in order to analyze real breakup processes. For this purpose, we have proposed a simple formula by using the complex scaling method and the validity of the new smoothing method was confirmed by test calculations for three-body breakup reactions. In a future work, we will investigate the practicability of this formula for four-body breakup processes.

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1. Abstract

A next-generation slow radioactive nuclear ion beam facility (SLOWRI) which provides slow, high-purity and small emittance ion beams of all elements is being build as one of the principal facilities at the RIKEN RI-beam factory (RIBF). High energy radioactive ion beams from the projectile fragment separator BigRIPS are thermalized in a large gas catcher cell. The thermalized ions in the gas cell are guided and extracted to a vacuum environment by a combination of dc electric fields and inhomogeneous rf fields (rf carpet ion guide). From there the slow ion beam is delivered via a mass separator and a switchyard to various devices: such as an ion trap, a collinear fast beam apparatus, and a multi-reflection time of flight mass spectrometer. In the R&D works at the present RIKEN facility, an overall efficiency of 5% for a 100A MeV ^{8}Li ion beam from the present projectile fragment separator RIPS was achieved and the dependence of the efficiency on the ion beam intensity was investigated.

First spectroscopy experiment at the prototype SLOWI was performed on Be isotopes. Energetic ions of ^{7,10,11}Be from the RIPS were trapped and laser cooled in a linear rf trap and precision spectroscopy was performed. The evaluated ion temperature of <10 mK demonstrates that a reduction of more than 15 orders of magnitude for the kinetic energy of radioactive Be was achieved online. Precise investigation of the hyperfine structure will confirm the anomalous mean radius of the valence neutron of the so called neutron halo nucleus.

Other spectroscopy experiments using the slow RI-beams are also under progress in off-line setups. A collinear fast beam apparatus for nuclear charge radii measurements was build and tested with stable Ar+ ion beams. A multi-reflection time-of-flight mass spectrograph was build for precise and fast measurements of short-lived radioactive nuclei. A high mass resolving power of 200,000 has been achieved with a 3 ms measurement period.

2. Major Research Subjects

(1) Development and constraction of the next-generation slow RI-beam facility
(2) Precision hyperfine spectroscopy of trapped ions for magnetization distribution in a halo nuclues
(3) Nuclear charge radii measurements using ion trap and collinear fast beam apparatus
(4) Precision mass measurements of short-lived nucei using a multi-reflection TOF mass spectrograph
(5) Development of deceleration and cooling devices for energetic beams using gas cell and rf fields.
(6) Atomic physics and fundamental symmetry research investigating nuclear decay of an isolated atom

3. Summary of Research Activity

(1) Development of universal slow RI-beam facility

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A next-generation slow radioactive nuclear ion beam facility (SLOWRI) which provides slow, high-purity and small emittance ion beams of all elements is being build as one of the principal facilities at the RIKEN RI-beam factory (RIBF). High energy radioactive ion beams from the projectile fragment separator BigRIPS are thermalized in a large gas catcher cell. The thermalized ions in the gas cell are guided and extracted to a vacuum environment by a combination of dc electric fields and inhomogeneous rf fields (rf carpet ion guide). From there the slow ion beam is delivered via a mass separator and a switchyard to various devices: such as an ion trap, a collinear fast beam apparatus, and a multi-reflection time of flight mass spectrometer. In the R&D works at the present RIKEN facility, an overall efficiency of 5% for a 100A MeV ^{8}Li ion beam from

the present projectile fragment separator RIPS was achieved and the dependence of the efficiency on the ion beam intensity was investigated.

(2) Laser spectroscopy of trapped radioactive beryllium isotope ions

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As a first application of the prototype SLOWRI setup, we are applying hyperfine structure spectroscopy to the beryllium isotopes to determine in particular the anomalous radius of the valence neutron of the neutron halo nucleus ^{11}Be, and to determine the charge radii of these beryllium isotopes through laser-laser double resonance spectroscopy of laser-cooled ions. Laser cooling is an essential prerequisite for these planned experiments. However, the exact resonance frequencies of the cooling transitions for radioactive beryllium isotopes are not known. In such light elements, the isotope shifts in the atomic transitions are larger than several 10 GHz and their dominant parts are due to complicated multi-electron correlations. Some theoretical works on the isotope shifts of the beryllium ion exist, however the values contradict each other at the level of accuracy needed.

The first laser spectroscopy experiments for beryllium isotopes were performed to measure the resonance frequencies of 2s $^2S_{1/2}$ - 2p $^2P_{3/2}$ transition of ^{7}Be+, ^{9}Be+, ^{10}Be$^+$ and ^{10}Be+ ions aiming at determining the nuclear charge radii. The hyperfine structure of ^{11}Be$^+$ and ^{7}Be$^+$ ions using the laser-microwave double resonance spectroscopy were also performed and A (^{7}Be$^+$)=-742.7723 (4) MHz and A (^{11}Be$^+$)=-2677.308 (2) MHz were determined for the first time. Precision measurements of the nuclear magnetic moments of these Be isotopes are in progress.

(3) Development of a multi-reflection TOF mass spectrograph

WADA, Michiharu, SCHURY Peter, TAKAMINE, Aiko, SONODA Tetsu, OKADA, Kunihiro, YAMAZAKI, Yasunori, WOLLNIK, Hermann,

The atomic mass is one of the most important quantity of a nucleus and has been studied in various methods since the early days of physics. Among many methods we chose a multi-reflection time-of-flight (MR-TOF) mass spectrometer. Slow RI beams extracted from the RF ion-guide are bunch injected into the spectrometer with a repetition rate of ~500 Hz. The spectrometer consists of two electrostatic mirrors between which the ions travel back and forth repeatedly. These mirrors are designed such that energy-isochrononicity in the flight time is guaranteed during the multiple reflections while the flight time varies with the masses of ions. A mass-resolving power of >200,000 has been obtained with about 500 reflections in a 30 cm length spectrometer. This mass-resolving power should allow us to determine ion masses with an accuracy of 10^{-7}. The advantages of the MR-TOF spectrometer are: 1) short measurement periods, typically 2 ms, which allows all neutron rich nuclei to be investigated, 2) the device is compact and its operation is simple, especially, it is independent from the all upstream devices, accelerators and fragment separators, 3) ions of more than isobars can be measured simultaneously, so that mass reference can easily be established in the mass spectra. In total, the number of measurable nuclides within a limited beam time would be larger than that can be achieved by other methods. It should be noted here also that this method can be used even during a low-duty parasite beam time. An on-line MR-TOF mass spectrograph with 80 cm length having an expected mass resolving power of 1,000,000 is under fabrication.

(4) Development of collinear fast beam apparatus for nuclear charge radii measurements

WADA, Michiharu, SCHUESSLER, Hans, IIMURA, Hideki, SONODA, Tetsu, SCHURY, Peter, TAKAMINE, Aiko, OKADA, Kunihiro, YAMAZAKI, Yasunori, WOLLNIK, Hermann,

The root-mean-square charge radii of unstable nuclei have been determined exclusively by isotope shift measurements of the optical transitions of singly-charged ions or neutral atoms by laser spectroscopy. Many isotopes of alkaline, alkaline-earth, noble-gases and several other elements have been measured by collinear laser spectroscopy since these ions have all good optical transitions and are available at conventional ISOL facilities. However, isotopes of other elements especially refractory and short-lived ones have not been

investigated so far.

In SLOWRI, isotopes of all atomic elements will be provided as well collimated mono-energetic beams. This should expand the range of applicable nuclides of laser spectroscopy. In the first years of the RIBF project, Ni and its vicinities, such as Ni, Co, Fe, Cr, Cu, Ga, Ge are planned to be investigated. They all have possible optical transitions in the ground states of neutral atoms with presently available laser systems. Some of them have so called recycle transitions which enhance the detection probabilities noticeably. Also the multistep resonance ionization (RIS) method can be applied to the isotopes of Ni as well as those of some other elements. The required minimum intensity for this method can be as low as 10 atoms per second.

We have built an off-line mass separator and a collinear fast beam apparatus with a large solid-angle fluorescence detector. A 617 nm transition of the metastable Ar+ ion at 20 keV was measured with both collinear and anti-collinear geometry that allowed us to determine the absolute resonant frequency of the transition at rest with more than 10^{-8} accuracy. Such high accuracy measurements for Ti and Ni isotopes are in progress.

Head
   Masanori WAKASUGI

Members
   Michiharu WADA

Nuclear Physics Research Division
Experimental Installations Development Group
SAMURAI Team

1. Abstract

This team is in charge of design, development and construction of the SAMURAI spectrometer that will be used for reaction experiments using RI beams at RI Beam Factory. SAMURAI consists of a large superconducting dipole magnet and a variety of detectors to detect charged particles and neutrons.

2. Major Research Subjects

Design, development and construction of the SAMURAI spectrometer at RI Beam Factory and its related research instruments.

3. Summary of Research Activity

This team is in charge of design, development and construction of the SAMURAI spectrometer at RI Beam Factory. Consisting of a large superconducting dipole magnet and a variety of detectors to detect charged particles and neutrons, SAMURAI will be used for various reaction studies with RI beams.

The research subjects may be summarized as follows:
(1)　Design, development and construction of a large superconducting dipole magnet that will be the main component of the SAMURAI spectrometer.
(2)　Design, development and construction of various detectors that are used for nuclear reaction experiments using the SAMURAI spectrometer.

Team Leader
　Toshiyuki KUBO

Members
　Hiromi SATO

Senior Visiting Scientist
　Toshio KOBAYASHI (Tohoku University)

Nuclear Physics Research Division
Experimental Installations Development Group
Polarized RI Beam Team

1. Abstract

The team conducts the research and development on the production of spin-oriented radioactive-isotope beams (RIBs), and applies it to the research on nuclear physics, fundamental physics, and material science. The microscopic investigation of physical and chemical processes is performed based on nuclear techniques which takes the advantage of intrinsic nuclear properties and phenomena (spins, electromagnetic moments, decay modes etc.). In particular, the precession/resonance of a polarized/aligned nuclear spin under an external field is observed through a change in the angular distribution of radiation, for the study of nuclear structures via nuclear moments. The experimental methods and devices for fundamental physics research with polarized nuclei have been also developed. The same method, as well as the Moessbauer technique, are used for the investigation of condensed matter such as semiconductor, ferromagnets, fullerenes, systems with dilute magnetic impurities etc. by capitalizing radioactive nuclei as microscopic probes into them. All these research activities are to be extended to wide variety of unstable nuclei which RI Beam Factory (RIBF) provides. A method to produce beams of highly polarized radioactive nuclei, taking full advantage of RIBF, is being developed.

2. Major Research Subjects

   (1) Nuclear-moment measurements of unstable nuclei
   (2) RIPS upgrade and the development of highly polarized slow RI beams
   (3) Fundamental physics: Study of symmetry
   (4) Condensed matter studies using radioactive nuclear probes

3. Summary of Research Activity

(1)   Nuclear-moment measurements of unstable nuclei

It has been revealed in our earlier work that spin-oriented RIBs can be obtained as a function of their outgoing momentum in the projectile-fragmentation reaction. With the obtained spin-polarized nuclei, ground- and excited-state nuclear moments can be determined by means of the β-NMR and TDPAD methods, respectively. Based on these technique, we have recently been conducted the nuclear-moments measurement of neutron-rich sd-shell around the neutron magic number N=20. It has been proposed in this region that an inversion of amplitudes between the sd normal and the pf intruder configurations would lead to deformation of the ground states. Thus, the region of nuclei is called the *island of inversion*. The measured nuclear moments are expected to provide microscopic properties for those nuclei of interest. The sub-themes are the following:

   ● Nuclear structure study of neutron-rich aluminum isotopes $^{30\text{-}32}$Al on the border of the *island of inversion* and $^{33\text{-}34}$Al on/beyond it.
   ● Investigation of a new *island of inversion* around N=28, the nuclear-moment measurements of neutron-rich isotopes.
   ● The ground-state electric quadrupole moment measurements of ^{23}Al for the study of the T=3/2 mirror symmetry.
   ● Study of nuclei around Fe region: isospin symmetry study by means of the magnetic moment of the 10^+ isomer in ^{54}Ni, and the study of magicity in the vicinity of ^{68}Ni through the quadrupole moment of the $13/2^+$ isomeric state in ^{69}Cu.
   ● Development of a new method to produce highly spin-aligned RIBs and a superconducting-magnet TDPAD system.

(2)   RIPS upgrade and the development of highly polarized slow RI beams

The upgrade of RIPS has been proposed in the phase-II programs. In the cyclotron-cascade acceleration scheme, beams are accelerated up to the energy of E=115 A MeV with IRC. In this upgrade, the former fragment separator RIPS is equipped with a new beam line that delivers beams of 115 A MeV heavy ions from the IRC cyclotron. RI beams produced by the primary beams at such an intermediate energy are high enough to produce RIBs via projectile-fragmentation reactions and suitably low in energy to be stopped in a sample material of limited thicknesses. Compared with the production yield of RIBs in the present AVF-RRC acceleration scheme, they are drastically increased. The design study of the upgrade program is in progress in our team. We noted that RIBs produced at E=115 A MeV can be spin-oriented so that the nuclear-moment measurements will be further conducted. Also, combining a new atomic-beam resonance method to combine with fragmentation-based RI beams, which is under development, to this program, highly spin-polarized RI beams will be produced in a low beam-energy region. Then, they could be useful not only for nuclear-moment measurements but also for spin-related subjects in nuclear physics, fundamental physics, and material sciences.

(3) Fundamental physics: Study of symmetry

Nuclear spins of stable and unstable isotopes sometimes play important roles in fundamental physics research. New experimental methods and devices have been developed for studies on the violation of time reversal symmetry (T-violation) using spin-polarized nuclei. These experiments aim detection of small frequency shift of the spin precession or measurement of the T-odd angular correlation in β-decay as T-violating signals arising from new mechanisms beyond the "Standard Model". Sub-themes are the following:

- Precision measurement of spin-precession frequency with a new type of the nuclear spin maser for atomic EDM (Electric Dipole Moment) search.
- Development of a new Mott polarimeter for T-violation experiment using β-decay of polarized unstable nuclei.

(4) Condensed matter studies using radioactive nuclear probes

Utilizing RI beams as a probe, online Mössbauer spectroscopy and online perturbed angular correlation experiments have been carried out through the γ-ray measurements. The microscopic structures, dynamics in ferromagnets, and properties of semiconductors have been investigated from the deduced internal local fields and the spin relaxation of the probe in materials. The β-NMR/NQR method is also utilized for these condensed matter studies. The methods and apparatus have been developed. Also, basic studies on the probe nuclei have been carried out. Sub-themes are the following:

- Study of "exotic" chemical states and the fast atomic-jump processes in solid with the online Mössbauer spectroscopy of implanted ^{57}Fe
- Development of the on-line perturbed angular-correlation method with ^{19}O beams as a new probe
- Study of the diffusion and segregation of Fe impurity atoms in Si through in-beam Mössbauer experiment with a Coulomb excited, recoil implanted ^{57}Fe nuclei.
- Study of the fast diffusion of Cu impurity atoms in Si through β-NMR/NQR with implanted ^{58}Cu.

Team Leader
   Masanori WAKASUGI

Members
   Hideki UENO
   Akihiro YOSHIMI
   Yuichi ICHIKAWA
   Yoshio KOBAYASHI

Nuclear Physics Research Division
Experimental Installations Development Group
Rare RI-ring Team

1. Abstract

We are developing the isochronous storage ring to measure the mass for rare radioactive isotopes (Rare RI ring). It is assumed that uranium is synthesized by neutron capture process after the supernovae explosion (r-process). To prove r-process, mass measurements for the rare RI are indispensable. To deduce the mass, we measure the circulation time (cyclotron frequency) for the rare RI inside the ring. RI beams produce in RIBF have some energy spread. To compensate the spread, isochronicity inside the ring is indispensable (isochronous storage ring). We will inject the rare RI one by one to the ring (individual injection) to identify the RI event-by-event. To perform the individual injection, we need a long injection line for the ring. The isochronous storage ring and the individual injection are very unique system.

2. Major Research Subjects

(1) Developments of isochronous storage ring to measure mass of rare RI.
(2) Developments of detectors for mass measurements and the related devices.

3. Summary of Research Activity

(1) Developments of isochronous storage ring to measure mass of rare RI

We are improving conceptual designs for an isochronous storage ring, kicker magnets, and the injection line to the storage ring. The storage ring consists of six sector magnets. The edge angles of each sector magnets compensate the first order isochronism. For the kicker magnets, we fixed rough specifications. For the injection line, we performed the first order ion-optical calculations. Furthermore, we performed magnetic field measurements of a present sector magnet in BigRIPS by using NMR with high accuracy.

(2) Developments of detectors for mass measurements and the related devices

Thin and fast timing detectors are developed. The group in Saitama University developed thin plastic-scintillators. They found that reasonably good timing resolution can be achieved even in the thin scintillator with 10 micron thickness. The group in University of Tsukuba developed Hybrid Photo Detector (HPD), which can replace with traditional Photo Multi Tube (PMT). Concerning to the related devices for the mass measurements, we started to develop cluster ion-source, that can be used for magnetic field calibrator in the storage ring.

Team Leader
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   Takeshi SUZUKI (Saitama University)

Takayuki YAMAGUCHI (Saitama University)
Takashi OHTSUBO (Niirata University)
Takashi KIKUCHI (Nagaoka University of Technology)

Nuclear Physics Research Division
Experimental Installations Development Group
SCRIT Team

1. Abstract

We aim at the investigation of internal nuclear structure of short-lived radioactive nuclei (RI) by means of electron scattering. Electron scattering for RI's has never been performed duo to inability to make target of these nuclei. An electron-RI collider system, which requires a huge accelerator complex, has so far been unique solution to overcome the difficulty. We have developed a novel internal target system named SCRIT (Self-Confining RI Ion Target) in an electron storage ring to make the experiment easier with much compact experimental system. An electron accelerator system required in this experiment will be constructed in next year, and the SCRIT device will be completed within the next two years.

2. Major Research Subjects

Development of the SCRIT technology and electron scattering for unstable nuclei

3. Summary of Research Activity

Development of a novel internal target of unstable nuclei (SCRIT) in an electron storage ring for electron scattering experiment

(Wakasugi, Suda, Ito, Emoto, Nakamura, Kurita, Tamae, Noda, Shirai, Yano)

We have successfully developed a novel internal target system, which is to be used in an electron storage ring. This is named SCRIT (Self-Confining Radioactive Ion Target). This technology can localize specific ions on the electron beam axis using so-called "ion-trapping" phenomenon and form a fixed target of unstable nuclei. This will realize electron-scattering experiments for short-lived nuclei that have never been succeeded in. In the R&D study of the SCRIT at the KSR in Kyoto University, we confirmed that approximately 10^7 of ^{133}Cs ions in the SCRIT device, and the angular distribution of elastically scattered electrons from the trapped Cs ions was measured. The collision luminosity was reached to be 10^{26} /cm^2/s, and the feasibility of electron scattering for unstable nuclei was completely demonstrated.

In last year, we moved the electron accelerator system, which consists of a 150-MeV microtron and an electron storage ring, to RIKEN from Sumitomo Heavy Industry Co. Ltd. They will be re-constructed and the SCRIT experimental system will be installed into the storage ring in 2009. We plan to start the electron scattering experiment for unstable nuclei from the beginning of 2011.

Team Leader
Masanori WAKASUGI

Members
Takashi EMOTO

Nuclear Physics Research Division
Experimental Installations Operation Group
GARIS Team

1. Abstract
  Development and maintenance of devices related to study of the superheavy elements.

2. Major Research Subjects
  (1) Maintenance and development of a recoil separator.
  (2) Development of rapid chemistry devices.

3. Summary of Research Activity
(1) Maintenance and development of recoil separator
  A gas-filled recoil separator has been used as a main experimental device for the study of superheavy elements. We will develop and maintain the related devices. We will also offer user-support if a researcher wishes to use the devices for his/her own research program.
(2) Development of devices for fast chemistry
  We do research and development of devices for fast chemistry of superheavy elements. We also offer user-support for potential users.

Team Leader
    Kouji MORIMOTO

Members
    Kosuke MORITA
    Daiya KAJI
    Akira YONEDA

Nuclear Physics Research Division
Experimental Installations Operation Group
BigRIPS Team

1. Abstract

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator and its related research instruments at RI beam factory (RIBF). They are employed not only for the production of RI beams but also the experimental studies using RI beams.

2. Major Research Subjects

Design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments

3. Summary of Research Activity

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer at RI beam factory (RIBF). They are employed not only for the production of RI beams but also various kinds of experimental studies using RI beams.

The research subjects may be summarized as follows:
(1) General studies on RI-beam production using in-flight scheme.
(2) Studies on ion-optics of in-flight separators, including particle identification of RI beams
(3) Simulation and optimization of RI-beam production.
(4) Development of beam-line detectors and their data acquisition system.
(5) Experimental studies on production reactions and unstable nuclei.
(6) Experimental studies of the limits of nuclear binding.
(7) Development of superconducting magnets and their helium cryogenic systems.
(8) Development of a high-power production target system.
(9) Development of a high-power beam dump system.
(10) Development of a remote maintenance and remote handling systems.
(11) Operation, maintenance and improvement of BigRIPS separator system, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer and so on.
(12) Design and construction of high-resolution beam line at RIBF.

Team Leader
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　Anthony NETTLETON (NSCL, Michigan State Univ., USA)
　Hans GEISSEL (GSI, Germany)
　Martin WINKLER (GSI, Germany)
　Michael FAMIANO (Western Michigan Univ., USA)
　Shashikant MANIKONDA (Argonne National Lab., USA)
　Yutaka MIZOI (Osaka Electro-Commnication Univ.)

Nuclear Physics Research Division
Experimental Installations Operation Group
Computing and Network Team

1. Abstract

Development, management and operation of the computing and network environment, mail server and data acquisition system and control of the information security of the Nishina Center for Accelerator-Based Science.

2. Major Research Subjects

(1) Development, management and operation of the computing
(2) Development, management and operation of the mail server
(3) Development, management and operation of the data acquisition system
(4) Development, management and operation of the network environment
(5) Control of the information security

3. Summary of Research Activity

Development, management and operation of the computing and network environment, mail server and data acquisition system and control of the information security of the Nishina Center for Accelerator-Based Science

Team Leader
Takashi ICHIHARA

Member
Yasushi WATANABE
Hidetada BABA

Nuclear Physics Research Division
Experimental Installations Operation Group
Detector Team

1. Abstract

This team is in charge of organizing various detector developments performed at in-house laboratories and groups, in order to improve mutual share of knowledge and experience. The team is also in charge of development and operation of cryogenic target systems used for nuclear physics experiments.

2. Major Research Subjects

(1) Development of delay-line PPAC.
(2) Development of transmitter/receiver for fast signal transmission through optical fibers.
(3) Design study of a micro strip silicon detector.
(4) Development and operation of cryogenic hydrogen and helium targets.

3. Summary of Research Activity

This team is presently focusing on developments of delay-line PPAC and fast signal transmission system consisting of optical fiber and a pair of fast transmitter and receiver. These two developments are essential for particle identification at BigRIPS separator and ZeroDegree spectrometer at RI Beam Factory (RIBF). The team is also in charge of development and operation of cryogenic target systems.

(1) Delay-line PPAC

At BigRIPS and ZeroDegree, a purity of radioactive isotope (RI) beams is as low as 10% or less at medium and heavy mass region. Thus, development of detectors for high-rate use is one of goals in this team. With this respect, we have developed a position-sensitive Parallel Plate Avalanche Counter (PPAC). Delay-line read-out technique appropriate for high rate use is employed for position determination. This PPAC has two stripped-electrodes for both horizontal and vertical positions, and this configuration leads to high performance in terms of efficiency as well as position resolution. More than ten PPACs have been installed at BigRIPS and ZeroDegree, and successfully used for RI-beam production and experiments.

(2) Fast transmitter and receiver for optical fiber.

In general co-axial metal wires are used for fast signal transmission. Instead, we have developed a special circuit for fast signal transmission through optical fibers, which consists of a pair of fast transmitter and receiver with a semiconductor laser and photo diode. At RIBF, circuits for detectors are located at several focal planes of the BigRIPS and ZeroDegree, and distances between focal-planes and counting room are as long as 100 m. The use of optical fibers for signal transmission allows us to focus on a common ground at each focal plane and easily isolate the ground levels.

The circuit has a fast time response of more than 1GHz. Attenuation of signal amplitudes is negligibly small even at a long distance transmission of more than 100m. Many sets of transmitter/receiver with an optical fiber have been manufactured and installed for detectors at BigRIPS and ZeroDegree, and successfully used for RI-beam production and experiments. This fast signal transmission scheme will be standard at RIBF.

(3) Design study of a micro strip silicon detector that will be used for SAMURAI spectrometer.

(4) Development and operation of cryogenic targets for nuclear physics experiments.

Development and operation of cryogenic targets, such as liquid hydrogen and helium targets and a solid hydrogen target, are very important for nuclear physics experiments using RI beams at BigRIPS and RIBF.

Team Leader
  Toshiyuki KUBO

Members
  Ken-ichiro YONEDA

Contract Researcher
  Kanenobu TANAKA
  Meiko UESAKA

Senior Visiting Scientist
  Hirohiko SHIMIZU (Inst.of Materials Structure Sci., KEK)

User Liaison and Support Division
User Liaison and Support Group
User Support Office

1. Abstract

The RIKEN RI Beam Factory is the world preeminent facility providing the greatest opportunities for scientific researches. The facility, completed its construction in 2007, has started its full-scale operation in the end of the year 2008. It is our important mission to serve for a broad range of application of a large variety of researchers so that we bring out the best performance of the RI Beam Factory. We manage to facilitate the use of RI Beam Factory to the researchers both inside and outside of RIKEN, to support experiments using the accelerator complex, to exploit industrial application researches, and to promote the RI Beam Factory to interested researchers

2. Major Research Subjects

  (1) Facilitation of the use of the RI Beam Factory
  (2) Support of experiments in the RI Beam Factory
  (3) Promotion of the RI Beam Factory to interested researchers

3. Summary of Research Activity

In order to facilitate the use of RI Beam Factory to the researchers both inside ad outside of RIKEN, we have organized international Program Advisory Committee, consisting of world leading scientists, to review proposals, purely based on their scientific merit and feasibility, in the fields of nuclear physics (NP) and material-and-life science (ML). The NP- and ML-PAC meetings are organized twice a year.

Team Leader
　Toshimi SUDA

Members
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　Narumasa MIYAUCHI

Assistant
　Tomoko IWANAMI
　Yuri TSUBURAI

User Liaison and Support Division
User Liaison and Support Group
Industrial Cooperation Team

1. Abstract

The scope of the industrial cooperation team includes industrial application of RIBF facility and research and development for industrial application of accelerator associated technologies.

2. Major Research Subjects

Distribution of radioisotopes Zn-65 and Cd-109 produced at RIKEN AVF Cyclotron and investigation of novel industrial applications of the accelerator beam and its related technologies

3. Summary of Research Activity

(1) Charged distribution of radioisotopes

At RIBF, various specific radioisotopes for research have been produced with the cyclotrons and used for various research projects. Since October 2007, we have distributed radioisotopes Zn-65 and Cd-109, which are produced by the RI application team at the AVF cyclotron, to nonaffiliated users under a Material Transfer Agreement between Japan Radioisotope Association and RIKEN.

(2) Feasibility study of RI-beam application in industries

To study feasibility of application of RI beam to industrial fields, research collaboration is being arranged with a private company.

Team Leader
 Tadashi KAMBARA

Members
 Tomoko ABE
 Hiroshige TAKEICHI

Visiting Scientists
 Makiko KAGA (National Inst. of Mental Health, Natl. Ctr. Neurol. Psychiat.)
 Atsuko GUNJI (National Inst. of Mental Health, Natl. Ctr. Neurol. Psychiat.)
 Michiteru KITAZAKI (Res. Center for Future Vehicle. Toyohashi Univ. of Tech.)

Student Trainees
 Kouta ARAI (Sakushin Gakuin Univ.)
 Shinichiro HARIYAMA (Dept. of Knowledge-based Information Eng., Toyohashi Univ. of Tech.)
 Shinichi ONIMARU (Dept. of Knowledge-based Information Eng., Toyohashi Univ. of Tech.)

Sub Nuclear System Research Division
Radiation Laboratory

1. Abstract

Nucleons, such as protons and neutrons, are a bound state of constituent quarks glued together with gluons. The detail structure of nucleons, however, is not well understood yet. Especially the mechanism to build up the spin of proton, which is 1/2, is a major problem in physics of the strong force. The research goal of Radiation Laboratory is to solve this fundamental question using the first polarized-proton collider, realized at RHIC, Brookhaven National Laboratory (BNL) in USA. RHIC stands for Relativistic Heavy Ion Collider, aiming also to create Quark Gluon Plasma, the state of Universe just after the Big Bang. RIKEN-BNL Research Center (RBRC) directed by N. Samios carries our core team at BNL for those exciting researches. Recent data analysis has shown that the proton spin carried by gluons is indeed small, which is a very striking finding beyond our expectations. We have been doing other pioneering researches at the domestic accelerators at SPring-8 and High Energy Accelerator Research Organization (KEK) which is now preceded to the new experiment at J-PARC. We are also performing technical developments such as novel ion sources, super conducting detectors, fine pitch pixel detectors and neutron optical devices.

2. Major Research subjects

1) Spin physics with relativistic polarized-proton collisions at RHIC
2) Study of nuclear matter at high temperature and/or at high density
3) Technical developments on radiation detectors and accelerators

3. Summary of Research Activity

(1) Experimental study of spin structure of proton using RHIC polarized proton collider
  [See: RIKEN-BNL Research Center Experimental Group]
(2) Experimental study of quark-gluon plasma RHIC heavy ion collider
  [See: RIKEN-BNL Research Center Experimental Group]
(3) Study of properties of mesons and exotic hadrons with domestic accelerators

Hadrons with more than three quarks are of great interest and have been looked for over the past 30 years. The Q^+ is a genuine exotic baryon with the minimum quark configuration of u, u, d, d and anti-s. After the first report on the evidence of the Q^+ at SPring-8/LEPS in 2002, evidence and counterevidence have been reported from all over the world, but its existence is not conclusive yet. We have made effort to establish the Q^+ since our first report. This year we reported again the observation of the Q^+ with clean and high statistics data at SPring-8/LEPS [Phys.Rev.C 79, 025210 (2009)]. In order to establish the Q^+ and explore the world of multiquark hadrons, R & D work is underway to construct LEPS-II, which is a new beam line and detectors at SPring-8.

Besides the Q^+, there is a long standing problem on the internal structure of the L (1405), whether 3 quarks, meson-baryon molecule or 5 quarks. In 2008, we measured the cross section of L (1405) photoproduction for the first time in the world. The data show strong enhancement near production threshold, and may suggest contributions of exotic production mechanisms related to the meson-baryon molecular structure of the L (1405) [PRC 78, 035202 (2008)].

Preparation of the experiment E16 at J-PARC 50-GeV PS is ongoing to obtain the full approval by PAC. The experiment aims to perform the systematic study of the mass modification of low-mass vector mesons in nuclei to explore the chiral symmetry in nuclear matter. GEM tracker and hadron-blind Cherenkov counter are being developed for the experiment. Required position resolution, approximately 100 micro meters, was achieved with a newly-developed flexible read-out board in a beam test of the tracker.

(4) Study of Accelerator and Ion source

To achieve highly polarized beams in RHIC it is necessary to understand the AGS (RHIC injector

synchrotron) spin dynamics. The normal-conducting partial-snake magnet, which we have developed for AGS years ago, is now in a stable operation with the other super-conducting snake magnet in AGS. After the departure of Researcher M. Okamura to BNL, this research category is moved to the collaborative work with BNL. Major equipments were transferred to BNL and became operational to continue the development of ion source with direct plasma injection scheme, with helps of two of our students.

(5) Detector development for PHENIX experiment

We have been developing the silicon vertex tracker (VTX) in order to enhance physics capability of the PHENIX detector at RHIC. It consists of two inner layers of pixel detectors and two outer layers of strip detectors. RIKEN Radiation Laboratory group is responsible for the ladder fabrication of the pixel detector. The production of high-signal-density low-material-budget flexible printed circuit board (bus) was started followed by a check procedure using dedicated test equipments. Prototype of the ladder was assembled on the fabricated bus and showed its functionality within the full PHENIX data acquisition chain. Also the assembly procedure with 10-micron accuracy was established

We also have been developing the momentum-sensitive trigger system for the PHENIX muon arms under the collaboration with KEK, Kyoto and Rikkyo University. About 200 circuit boards for the new trigger system were installed to a half of the muon arm acceptance and they are planned to be commissioned during the experiment in 2009.

(6) Research and development of superconductor radiation detectors

Superconductor radiation detectors are able to measure the energies of photons with a much better resolution than any type of conventional detectors. They are capable of detecting photons over a wide energy range and also charged particles. We have been developing superconducting tunnel junctions (STJs) as high-resolution radiation detectors. This year, we continued the collaborations between KEK and University of Tsukuba. With KEK, we succeeded in fabricating Aluminum-based-STJ (Al-STJ) which was free from a damage due to heat cycle. The sub-gap current of these STJs were almost uniform and they were consistent with calculated values from the BCS theorem. With Univ. of Tsukuba, we continued to study basic fabrication methods in order to make Hafnium-based-STJ (Hf-STJ). We found that Hf can be etched with ICP reactive etching method. An obtained etching speed was 31nm/min and this is enough to fabricate Hf film. We have started to make Hf-STJ structure. So far, unfortunately, we don't succeed in fabricating proper tunnel junctions.

We have decided to close this activity in Radiation Laboratory and transferred all the equipments to KEK. Our technologies to fabricate STJ are inherited by KEK and Univ. of Tsukuba.

(7) Neutron optics

Cold or thermal neutron beam is a high-sensitivity probe to study not only the structure of condensed matter, but also nuclear and particle physics. However, its realistic applications are still limited since the numbers of available neutron sources are small and their intensities are low. This project aims to enhance the efficiency in using those precious neutron beams by improving the neutron beam optics, in order to maximize scientific outputs within a short period of time. Base on the developed technologies, devices are fabricated and distributed to other laboratories and universities by "Riken Venture Company", Japan Neutron Optics Inc.

This year, we successfully observed the first signal for fundamental physics research in a new beam line at 1MW Pulse Spallation Neutron Source in J-PARC. This beam line was designed by applying our knowledge and technique of neutron optics. We also succeed to observe interference signals of cold neutrons using the Si crystal interferometer at JRR-3M. There, we are developing a new type of instrument for phase-difference imaging with use of the gratings developed by us. We are also planning to study neutron Electron Dipole Moment using a perfect crystal at the J-PARC beam line.

(8) Theoretical study of hadron physics

Nuclear matter at finite temperature and density was studied in lattice simulations of quantum chromodynamics (QCD) which is the first principle to describe the interactions of quarks and gluons. Several

experimental properties of a QCD phase transition from a hadronic matter to quark-gluon plasma, suggested by relativistic heavy-ion experiments at RHIC, were investigated with calculations of Polyakov-loop and quark number susceptibilities. A new approach to calculate the equation of state was derived and developed in the full-QCD simulations which include dynamical quarks of up, down and strange flavors.

Strong correlation in QGP was also studied in the lattice QCD simulation. Calculating correlation functions between Polyakov-loop operators, the free energy and potential between heavy quarks were extracted and confinement properties before and after the deconfinement transition and screening effects in the electric and magnetic sectors were investigated. Dissociation temperature of a charmonium bound state in QGP was also investigated in a multi-state variational analysis.

The fragmentation functions for the proton and the pion are studied using the Nambu-Jona-Lasinio (NJL) model. The Drell-Levy-Yan (DLY) relation, which connects the fragmentation functions with the quark distribution functions, is used to select the diagrams. The calculated fragmentation functions are Q^2 evolved to be compared with the results of global analyses. The calculation gives too small fragmentation functions both for protons and pions. It is also found that the DLY relation could be violated by the cut-off procedure and the Q^2 evolution may develop a singularity at x=1. Attempts to improve the choice of diagrams are now in progress.

In connection with the hot QCD, the particle emission and absorption in a uniformly accelerated frame are studied. The canonical quantization for the Maxwell field is formulated in general static space-time geometries and is applied to the case of the Rindler space-time corresponding to the uniformly accelerated frame. The Unruh effect is confirmed and its implications to RHIC physics are discussed. The effects of the uniform acceleration on the Coulomb potential are also studied and the possible ways of observing them in the hydrogen spectra are discussed.

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1. Abstract

Particles like muons, pions, and kaons have finite life times, so they do not exist in natural nuclei or matters. Implanting these particles into nuclei/matters, exotic phenomena in varieties of objects can be studied from a new point of view.

Kaon is a second lightest meson which has strange-quark as a constituent quark. It is expected that if one embed a kaon into nuclei, the sizes of the nuclei become smaller and forms a high density object beyond the normal nuclear density. Study of this object could lead better understanding of the origin of the mass of the matter, and may reveal the quark degree of freedom beyond the quark-confinement. Those properties can be studied by precise heavy pionic atom research in different angle. The other example is the weak interaction in nuclear matter. It can only be studied by the weak decay of hypernuclei, which have Lambda particle in the nuclei,

Muon provides even wider variety of study from nuclear reaction to magnetism in matter. For instance, stopping positively charged muon in a material, we obtain information on the magnetic properties or the local field at the trapped site. Injecting negatively charged muon to mixture of deuterium and tritium, muon attracts surrounding atoms and is known to cause d-t fusions.

As is already clear, in our research we introduce different kind of impurities into nuclei/matters, and study new states of matter, new phenomena, or the object properties.

2. Major Research Subjects

(1) Study of meson property and interaction in nuclei
(2) Origin of matter mass / quark degree of freedom in nuclei.
(3) Condensed matter and material studies with muon
(4) Nuclear physics via muon catalyzed fusion and muonic atoms

3. Summary of Research Activity

Hadron physics at J-PARC and RIKEN-RIBF

Kaon and pion will shed a new insight to the nuclear physics. The recent discovery of deeply bound pionic atom enables us to investigate the properties of mesons in nuclear matter. At RIKEN-RIBF, we are preparing precise experimental study of the pionic atom. We are intensively preparing another next generation kaon experiments (E15 and E17) at J-PARC as day-one experiments. In these experiments, we are aiming at precise determination of the KN interaction, and clarify the nature of kaon in nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

1) Deeply bound kaonic nuclei

We have performed a high precision and small ambiguity spectroscopy on the K-ppn system, strange tribaryon -S°(3115)-, at KEK (High energy accelerator research organization). We measured the momenta of protons emitted in the reaction between negatively charged K mesons and helium nuclei. Compared to the previous experiment, the mass resolution was improved by a factor of 2 and the statistical accuracy by a factor of about 10. We have newly installed detectors exclusively used for the measurement of the protons and realized small-ambiguity experiment. As a result, no structure was observed, in the spectrum, associated to the strange tribaryon with the natural width of 20 MeV/c^2, and the result was contradictory to the previous experiment. Statistical evaluation tells that the previous results are rejected by 99% confidence level. The experiment also tells us that the difficulty of the bound state search using at rest reaction, in which non-mesonic two-nucleon absorption reactions produce huge energetic nucleon background in the energy region of interest. This two-nucleon absorption process also caused the absorption width of he kaonic bound state. Thus we proceed the search of the state in the simplest system K-pp at the kaon incident momentum of 1

GeV/c as a day-one experiment at J-PARC.

2) Deeply bound pionic and eta- nuclei

We made a spectroscopy experiment to measure deeply bound pionic states in several tin isotopes at the GSI, Germany, to investigate the pion-nucleus strong interaction. The results provided information on the iso-vector part of the strong interaction between pion and nucleus. More advanced discussion leads to the origin of the mass of matter, which is attributed to the quark condensation in the vacuum. Presently we have been working on preparation for the experimental study of pionic atoms at RIKEN-RIBF.

3) Precision X-ray measurement of kaonic atom

Simultaneously with the above experiment (1), we have performed an X-ray spectroscopy of atomic $3d \rightarrow 2p$ transition of negatively charged K mesons captured by helium atoms. Many Kaonic atoms are known to be measured with various elements, however, there are very large deviations in the measured energy levels for the helium (and the oxygen) from the systematic expectations. The deviation originates in technical issues in old experiments, and new and high precision data have been long awaited for. Also, wave functions of the Kaonic atoms are expected to reflect the information on the existence of the inner structure, namely deeply bound Kaonic states. As a result of the experiment, we have succeeded in performing the spectroscopy and achieved the shift of 2+-2(stat.) +-2(syst.) eV. The obtained results reject older data beyond any doubt, and the above deviation is dissolved. Presently, aiming at the determination of the level width and yield, we are analyzing the data. To clarify the KN interaction strength, we are preparing another x-ray measurement of the kaonic helium-3 atom, which is another day-one experiment at J-PARC.

Muon science at RIKEN-RAL branch

The research area ranges over particle physics to condensed matter studies and life science. Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford Appleton Laboratory (UK), which provides the most intense pulsed muon beam. We have variety of important research activities such as muon-catalyzed fusion (mCF) and condensed matter physics by muon spin rotation / relaxation / resonance (mSR).

(A) Condensed matter/materials studies with mSR

A major upgrade work for mSR facility is being carried out at RIKEN-RAL muon facility reflecting growing number of collaborations with other universities and research institutes in this field. A pulsed laser system, which consists of a Nd:YAG laser and an OPO laser, was installed under collaboration between the University of Yamanashi, KEK, and RIKEN. The laser system is now used for the mSR to study effects induced by intense photon field, such as spin polarization of conduction electrons in semiconductors. A new mSR spectrometer, which will enable us to study a sample under multiple-extreme condition, was built and is about to be installed in the beam area.

There are three topics of material sciences studied by the muon-spin relaxation method at the RIKEN-RAL Muon facility in 2008.

1) The dynamics of the charge transfer in an ion mixed-valence complex, $(n\text{-}C_3H_7)_4N[Fe^{II}Fe^{III} (dto)_3]$ ($dto=C_2O_2S_2$), has been investigated. The oscillation of an electron with slow frequency of the order of kHz in between two iron sites has been firstly observed and quantitative value of the frequency has been achieved.

2) The dynamics of the internal field at the muon site in the high-T_c superconducting oxide, $La_{2-x}Sr_xCuO_4$, has been investigated by precise mSR measurements. A change of the dynamics of the internal field at higher temperature than the superconducting and magnetic transition temperatures has been observed. A model-relationship with a spin-gap state which is important to describe the superconducting gap of high-T_c oxides has been suggested.

3) A co-existing relationship between a magnetically ordered state and the superconducting state in a newly found Fe-based superconducting oxide has been clarified. An important role of the magnetism for the superconductivity has been suggested.

(B) Nuclear physics studies with muons, such as muon catalyzed fusion and muonic atoms

1) Muon catalyzed fusion (mCF)

We are studying the muon catalyzed fusion (mCF) processes in a wide range of hydrogen target conditions such as isotope mixtures and temperatures. This year we designed a test high pressure target, which will enable us to keep D_2 target in solid state up to 30 K, thus we will be able to study mCF in high density and high temperature solid target, where the mCF is expected to occur much faster than in liquid.

2) Development towards muonic atom formation with unstable nuclei

Stopping negative muons in the solid hydrogen with implanted unstable atoms, muons transfer efficiently to the implanted nuclei from muonic hydrogen to form the muonic atoms. By observing muonic X-rays at muonic atom formations, fundamental experiments on the nuclear charge density distribution are in progress. Using the newly installed surface ionization ion source, we carried out successfully the experiment to measure isotope energy shifts of muonic X-rays originated from muonic ^{86}Sr, ^{88}Sr, ^{88}Sr, ^{138}Ba, ^{148}Sm and ^{152}Sm atoms.

3) Generation of ultra slow positive muon beam

Low energy muon beam, whose kinetic energy is variable from a few keV to a few tens of keV, will extend the scope of mSR technique from a bulk material to surfaces and multi-layered materials. It is also expected that a very sharp beam of low energy muon may enable a new way of precision measurement of muon's anomalous gyro-magnetic ratio (g-2). Following the successful generation of slow muon beam by laser ionization of thermally emitted muonium in vacuum, we plan to increase the slow muon beam intensity by more than 100 times. For this purpose, we have started upgrading works on the slow muon beam such as a new intense laser system, more efficient muonium production targets, and new control system of the slow muon beam line.

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Sub Nuclear System Research Division
Theoretical Physics Laboratory

1. Abstract

The aim of this laboratory is to reveal the laws of nature ranging from elementary particles to the universe. More precisely, the following three issues are pursued with their mutual relations emphasized: (1) Understanding the microscopic fundamental law of nature. In particular, trying to give a consistent definition of superstring and derive all the fundamental laws from one principle. (2) Understanding many-body systems. Both of the following two aspects are considered. One is the universal laws such as thermodynamics and the universality of spin systems, and the other is specific properties of individual systems such as hadrons, condensed matter, and the universe. (3) Computational science. Besides numerical analyses as an important tool for the above mentioned (1) and (2), aspects of fundamental mathematics are also pursued.

2. Major Research Subjects
(1) Constructive Definition of String Theory as Fundamental law of Physics
(2) Fundamental aspects of Quantum Field Theory and its applications
(3) High precision inspection of experimental and observational data

3. Summary of Research Activity

The ability to understand nature at its most profound level is a basic human desire. Science is founded on accumulated and tremendous efforts driven by that aspiration. The objective of our laboratory is to participate in the endeavor to better understand nature by adding our contributions to theoretical physics. The present seems to be a particularly exciting time for this as many developments appear to be about to converge and allow formation of the ultimate theory of everything.

We organize our research activities into three segments: the pursuit of the microscopic fundamental laws of physics, the study of many-body systems, and the science and technology of computation. These three aspects have an inseparable interrelation and are investigated in an integrated manner throughout the research conducted within this laboratory.

(1) Understanding the fundamental law of nature through string theory.

  1) Non-perturbative effect for non-critical string

The analysis of the nonperturbative effect in the $c=0$ noncritical string theory defined by the one-matrix model is extended to the case of two-matrix models which provide nonperturbative definitions of $c<1$ noncritical string theories. Then, universality of nonperturbative effects including their coefficients in a generic $c<1$ noncritical string theory is achieved in the sense that they are independent of details of potentials of the two-matrix models.

  2) Matrix models and curved space-time

Incorporating curved space time into matrix models is pursued. In particular, a method in which larger additional degrees of freedom is introduced to represent space-time symmetry, is proposed.

  3) Domain Wall in string theory

We investigate a global structure of the moduli space of the BPS domain wall system. I particular, we are interested in the case where the dimensions of the moduli space is greater than those expected from the index theorem. We also study the T-duality between the vortices and domain walls from a string theoretical point of view. We explicitly construct a vortex solution in the Higgs phase of supersymmetric gauge theory and find an exact correspondence between the solution and D-brane configuration in the domain wall side.

  4) Non BPS branes and supergravity

We investigate the correspondences between a class of classical solutions of Type II supergravity (the three-parameter solution) and D-branes in the superstring theory. In addition to the mass, the RR-charge, the solution also carries the so-called dilaton charge, whose physical meaning was unclear. We find that the

appearance of the dilaton charge is a consequence of deformations of the boundary condition from that of the boundary state for BPS D-branes. We also show that such deformed boundary states are realized as tachyonic and/or massive excitations of the open strings on D-brane systems.

5) D-branes and instantons

We have investigated instantons of four-dimensional SUSY gauge theory from the view point of superstring theory. A general prescription to construct the instanton solutions is known as the ADHM (Atiyah-Drinfeld-Hitchin-Manin) construction. In terms of superstring theory, instanton is understood as a bound state of D3-branes and D (-1) -branes. We consider a system of D3-branes and anti-D3-branes to construct the bound state via a tachyon condensation. As a result, we found that the tachyon profile contains all information on the instanton and the ADHM construction can be understood as an outcome of the gauge equivalence of this system in the low energy limit. We also applied the same method to eight-dimensional gauge theory and showed that some solitonic solution of the eight-dimensional theory can be constructed by this method.

6) Application of string theory to cosmology

Cosmological scenarios alternative to inflation motivated by string theories are known. In cyclic scenario, or ekpyrotic scenario, the universe is considered as branes sitting in higher dimensional space time. The universe is assumed to start out from a static Minkowskian space-time and experience the big-bang as the collision of pair of branes (bounce). From the observational point of view, it is of importance to study the time evolution of cosmological fluctuation through the time of big bang. We studied the problem from the point of view of local causality through the bounce. Assuming the local causality condition, we derived the most general matching condition for the fluctuation between before and after the bounce. Especially, we found it is impossible to generate scale invariant spectrum without introducing non-local causality throughout the bounce. This work made clear the physical problem to obtain the scale invariant spectrum in the bouncing cosmology. We have also studied a toy model inspired by a low-energy effective action of non-commutative field theory and estimated the range of parameters to obtain scale invariant spectrum.

Another subject pursued was the possibility of obtaining inflation due to the modification of the dispersion relation. When non-equilibrium dynamics is taken into account, we observed that the inflation can be easily realized when the energy is a decreasing function of the momentum in high-energy regime. This result provides alternative way of realizing inflation in the framework of unified theory.

7) Application of string theory to Nuclear physics

Holographic QCD, which is the application of the AdS/CFT correspondence to QCD, turns out to be a very fruitful arena of research in string theory. Using holographic QCD technique, various quantities which are difficult to calculate by perturbative QCD, lattice QCD and conventional nuclear physics approach are investigated. For example, the decay rate of f0(1500) is calculated suggesting its connection to much sought glueballs.

(2)   Quantum field theory and physics of many body systems

1) Lattice formulation of supersymmetric gauge theory

We proposed a lattice formulation of low dimensional supersymmetric gauge theories, aiming at practical implementation for numerical simulations.

2) Lattice formulation of fermions coupled to gravity

We formulated lattice Dirac operator of the overlap-type that describes the propagation of a Dirac fermion in a gravitational field. We also analyzed global gauge anomalies associated with Majorana fermions in 8k and 8k+1 dimensions.

3) Mathematical aspects of 2-dimensional gauge theories and string.

We investigate a non-perturbative correction to the N=2 supersymmetric Yang-Mills theory from the discrete matrix model point of view. We utilize the D-brane picture in superstring theory and localization theorem in order to derive the discrete matrix model from 2-dimensional Yang-Mills theory on a compact 2-cycles in the ALE space. We also find the relationship to the Dijkgraaf-Vafa theory in the continuum limit.

4) Logarithmic Confromal Field Theory

The following topics are investigated: Free field representation for LCFT with boundary; The relation between Minimal String theory and LCFT; The relation between statistical models and LCFT.

5) Quantum field theory over the deformed commutation relation

A quantum theory of free scalar field based on the deformed Heisenberg algebra which is the correction of stringy physics is constructed.

6) Chern Simons Yang Mills Model

We have studied the Chern Simons Yang Mills Model. Non-commutative gauge theories on fuzzy spheres were obtained in such models. Fuzzy spheres look like dbrane configuration. k coincident fuzzy spheres generates the $U(k)$ gauge group. In this direction, we are continuing effort to address some of the related issues.

(3) High precision calculation of field theory and computational science

1) High precision calculation of QED

We have announced the final result of our calculation of the electron anomalous magnetic moment. It contains up to the eighth-order of the perturbation theory of QED. The very reliable result was obtained by using high precision calculation on RIKEN's supercomputer system (RSCC).

We also succeeded in automating the calculation of the tenth-order of the perturbation theory, particularly in constructing the ultra-violet subtraction terms. This is an important step to accelerate our calculation of the entire tenth-order contribution.

The dominant contribution from the tenth order to the muon anomalous magnetic moment was also announced by us. In contrast to the electron, some specific Feynman diagrams give rise to the large contributions to the muon anomaly. We explicitly evaluated about 2000 Feynman diagrams which are possible to give the leading and next-to-leading contributions.

2) Improved perturbation method and its applications

We apply improved perturbation method which is one of the variational schemes to Ising model in two-dimensions. It enables us to evaluate free energy and magnetization at strong coupling regions from weak coupling expansion even in the presence of the phase transition.

We determine approximated transition point in this scheme. In the presence of external magnetic field we can see not only stable physical states but metastable one. This reserach motivated by availability of this method to IIB matrix model which is expected to show a phase transition from 10-dimensional universe to 4-dimensional universe.

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1. Abstract

We proposed accurate few-body calculational method called "Infinitesimally shifted Gaussian lobe method". Recently, we developed this method to four-body systems and five-body systems. This method is applicable for various three-and four-body systems. For example, we applied it to hypernuclear physics and clarified what is important and impressed. In fact, we applied this method to three kinds of hypernuclear experiments (KEK-E419, BNL-E930, and -E929) in the past, and we contributed to these experiments by discussing with experimentalists, analyzing the data, and interpreting the data.

2. Major Research Subjects

(1) Hypernuclear structure from the view point of few-body problem
(2) Structure of exotic hadron system
(3) Baryon-baryon interaction based on lattice QCD

3. Summary of Research Activity

(1) Detailed structure calculations in $^{12}Be_\Xi$, $^{5}H_\Xi$, $^{9}Li_\Xi$, $^{7}H_\Xi$ and $^{10}Li_\Xi$ are performed within the framework of the microscopic two-and three-and four-body cluster models using Gaissian Expansion method. $^{7}H_\Xi$ and $^{10}Li_\Xi$ are predicted to have bound stats. Then, we propose to observe the bound states in future (K-, K+) experiments using ^{7}Li and ^{10}B target after Day-1 experiment at J-PARC facility.

(2) The potential between proton and Ξ are obtained using quenched lattice QCD simulation. As a result, we found that the central $p\Xi^0$ potential has a strong (weak) repulsive core in the 1S0 (3S1) channel for r<0.6fm.

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Accelerator Applications Research Division
Accelerator Applications Research Group
Radiation Biology Team

1. Abstract

Radiation biology team studies various biological effects of fast heavy ions. It also develops new technique to breed plants by heavy-ion irradiations. Fast heavy ions can produce dense and localized ionizations in matters along their tracks, in contrast to photons (X rays and gamma rays) which produce randomly distributed isolated ionizations. These localized and dense ionization can cause double-strand breaks of DNA in cells which are not easily repaired and result in mutation more effectively than single-strand breaks. A unique feature of our experimental facility at the RIKEN Ring Cyclotron (RRC) is that we can irradiate living bodies in atmosphere or in bottles since the delivered heavy-ion beams have energies high enough to penetrate deep in matter. This team utilizes a dedicated beam line (E5B) of the RRC to irradiate cultivated cells, plants and animals with beams ranging from carbon to iron. Its research subjects cover physiological study of DNA repair, genome analyses of mutation, and development of mutation breeding of plants by heavy-ion irradiation. Some new cultivars have already been brought to the market.

2. Major Research Subjects

(1) Study on the biological effects by heavy-ion irradiation
(2) Studies on ion-beam breeding and genome analysis
(3) New medical application of heavy-ion beams

3. Summary of Research Activity

We study biological effects of fast heavy ions from the RIKEN Ring Cyclotron using 135 MeV/N C, N, Ne ions, 95 MeV/N Ar ions and 90 MeV/N Fe ions. We also develop breeding technology of plants. Main subjects are:

(1) Study and application of heavy-ion induced plant mutation

In contrast to X rays and gamma rays, fast heavy ions are found to be useful for plant breeding since they only cause localized damage on DNA and can induce mutations more effectively with lower dosage. Our team utilizes beams of fast heavy ions from the RIKEN Ring Cyclotron to develop heavy-ion breeding techniques. Genome analyses are performed to reveal the relation between genotype and phenotype.

(2) Study of heavy ion-induced damage of DNA and its repair processes

We study the double-strand break of DNA induced by heavy-ion irradiation and its repair processes. DNA double strand break (DSB) is characteristic to heavy-ion irradiation and considered to be the characteristic lesion responsible for its biological effects. Cells have two pathways to repair DSB, non-homologous end-joining (NHEJ) and homologous recombination (HR), and it is unknown how the two pathways are involved in repairing the damage caused by heavy-ion irradiation. To elucidate it, we irradiate higher vertebrate cells lacking DNA repair proteins with C, Ar, or Fe ions and analyze them with colony formation assay and molecular biology methods.

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Accelerator Applications Research Division
Accelerator Applications Research Group
RI Applications Team

1. Abstract

RI Applications Team performs following researches at the heavy ion accelerators of RIBF: (1) With proton from the RIKEN AVF Cyclotron, we produce radioisotopes for research of chemistry, biology, medicine, pharmaceutical and environmental sciences. The nuclides Zn-65 and Cd-109 are delivered to Japan Radioisotope Association for charged distribution to the general public in Japan. We also study the production and application of short-lived RI's. (2) We develop new technologies of mass spectrometry for the trace-element analyses using accelerator technology and apply them to the scientific research fields, such as cosmochemistry, environmental science, archaeology and so on.

2. Major Research Subjects

(1) Production of radioisotopes Zn-65 and Cd-109 for charged distribution,

(2) Research and development for new RI production at AVF cyclotron,

(3) The development of trace element analysis, using the accelerator techniques, and its application to geo and environmental sciences

3. Summary of Research Activity

RI applications team utilizes RIBF heavy-ion accelerators for following research subjects:

(1) Production of radioisotopes

Using 14-MeV proton beam irradiations at the RIKEN AVF Cyclotron, we develop techniques of production and application of various radio-isotopes (RI's) for research in chemistry, biology, medicine, pharmaceutical and environmental sciences. We can produce RI's with wide range of lifetimes as short as seconds. Long-life (>a few days) RI's are produced in a target which is cooled by water and He gas, and short-life RI's are produced at a gas-jet system where RI atoms are recoiled out of thin foil targets, captured by KCl aerosols and transported to a hot lab by a flow of He carrier gas. These systems are in the same chamber and can operate in parallel with the same beam. Among the long-life RI's, Zn-65 ($T_{1/2}$=244 days) and Cd-109 ($T_{1/2}$=463 days) are delivered to Japan Radioisotope Association for charged distribution to the general public in Japan.

(2) R/D for RI production

We work to improve production procedure of the present Zn-65 and Cd-109 for stable supply and better quality. We also develop production techniques for other RI species which are demanded but lack supply sources. The collection efficiency of gas-jet system has been optimized for Zr-89m ($T_{1/2}$=4.16m), Nb-90m ($T_{1/2}$=18.8s) and Nd-141m ($T_{1/2}$=62s) nuclides.

(3) Trace element analyses with accelerator technologies

We have developed two new technologies of mass spectrometry for the trace-element analyses as an application of accelerator technology to various fields such as cosmochemistry, environmental science, archaeology and so on. On is a new type Accelerator Mass Spectrometry (AMS) at the RILAC equipped with an ECR ion source. This system is available for the measurements of trace-elements (10^{-14}-10^{-15}level), and is expected to be especially effectible for the measurements of low electron-affinity elements such as ^{26}Al, ^{41}Ca, ^{53}Mn and so on. As a preliminary study, the ECR ion source system has been evaluated and the basic data have been obtained for the detection and quantitative analysis of trace nuclides in archaeological samples (cinnabar) and functional metals. As another technology, we have attempted to customize a mass spectrometer equipped with a stand-alone ECR ion source for analyses of elemental and isotopic abundances.

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Safety Management Group

1. Abstract

The Nishina Center for Accelerator-Based Science possesses one of the biggest accelerator facilities in the world which consists of a heavy-ion linear accelerator and 5 cyclotrons. Uranium ions are accelerated here only in Japan. Our function is to keep the radiation level in and around the facility below the allowable limit and to control the exposure on the workers as low as reasonably achievable. We are also involved in the safety management of the Radioisotope Center where many types of experiments are performed with sealed and unsealed radioisotopes.

2. Major Research Subjects

(1) Safety management at radiation facilities of Nishina Center for Accelerator-Based Science
(2) Safety management at Radioisotope Center
(3) Radiation shielding design and development of accelerator safety systems

3. Summary of Research Activity

Our most important task is to keep the personnel exposure as low as reasonably achievable, and to prevent an accident. Therefore, we daily patrol the facility, measure the ambient dose rates, maintain the survey meters, shield doors and facilities of exhaust air and wastewater, replenish the protective supplies, and manage the radioactive waste. Advice, supervision and assistance at major accelerator maintenance works are also our task.

We installed radiation safety interlock system at the newly built RIBF building, and are extending it along with the constructions of experimental facilities. The suffocation-safety interlock system was also installed at the BigRIPS tunnel of RIBF accelerator building where huge amount of liquid He is used for superconducting magnets. The radiation safety interlock system for Nishina building was recently replaced by a simple and reliable one with a new concept.

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RIKEN-BNL Research Center
Theory Group

1. Abstract

   The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory in New York, USA. The Center is dedicated to study of strong interactions, including hard QCD/ spin physics, lattice QCD and RHIC physics through nurturing of a new generation of young physicists. The Theory Group activities are closely and intimately related to those of the Nuclear Theory, High Energy Theory and Lattice Gauge Theory Groups at BNL. The RBRC theory group carries out research in three areas: numerical lattice QCD, perturbative QCD and phenomenological QCD. It pioneered the use of the domain-wall fermion method in lattice QCD and has investigated various aspects of hadron physics including the calculation of neutral Kaon CP-violations that is relevant for checking the Cabibbo-Kobayashi-Maskawa theory. The perturbative QCD effort has developed various new methods required for studying hadron structures, especially in spin physics research. The group has pioneered phenomenological QCD researches of color superconductivity, isospin density, and small-x phenomena in extreme hadronic matters.

2. Major Research Subjects
   (1) Perturbative QCD
   (2) Lattice QCD numerical research
   (3) Phenomenological QCD

3. Summary of Research Activity

   The RIKENBNL Research Center (RBRC) was established in 1997 to support the RIKEN activities at RHIC in BNL, and also to promote theoretical studies related to RHIC, i. e. theories of strong interaction. The center's first director was T. D. Lee (Columbia University), and in October 2003, the former director of BNL, N. P. Samios, succeeded to the post of director. H. En'yo, Chief scientist of RIKEN in Wako, is also associate director of RBRC. The center consists of a theory group lead by L. Mclerran (BNL) and an experimental group lead by Y. Akiba of RIKEN, currently resident at BNL.

   Research in the RBRC theory group focuses on a wide variety of phenomena caused by the strong interaction, one of the four fundamental interactions in nature. The strong interaction is described theoretically by Quantum Chromodynamics (QCD), and the research projects in the RBRC theory group aim to elucidate various phenomena brought about by the strong interaction from the principles of QCD. Major subjects of our research include studies (a) based on lattice QCD, (b) on spin physics based on perturbative QCD, and (c) on QCD in extreme conditions such as high temperature, high density or high energy. RBRC offers RHIC Physics Fellowships, allowing joint appointments with universities. These Fellowships enable a talented researcher to maintain a tenure track position at his/her university as well as a Fellow position at RBRC for a certain period of time. This system was established in order to increase the research potential of RBRC and to disseminate its research activities and results. At present, RBRC has cooperative agreements with Arizona State University, the City University of New York, Iowa State University, Purdue University, Pennsylvania State University, the State University of New York at Stony Brook, Texas A&M University, the University of Tsukuba, as well as with BNL and with Lawrence Berkeley National Laboratory.
(1) Lattice QCD
   QCDOC (QCD on chip), a second-generation lattice-QCD computer, was developed in the collaboration amongst the RBRC group, Columbia University and IBM. Three units of such a machine with 10 teraflops computing power are in operation since 2005; two in BNL (RBRC and DOE) and one in Edinburgh (UK-QCD), and formed a world-wide strong collaboration for the lattice QCD studies. Such computing power enables us to perform precise calculations with 3 quark flavors with proper handling on the chiral symmetry breaking. Several projects are ongoing: flavor physics for Kaon and B-meson, electro-magnetic properties of

hadrons, proton decay, the nuclear force, nucleon form factors which relates to the proton spin problem, and QCD thermodynamics in finite temperature/density systems as is produced in RHIC heavy-ion collisions. R and D led by the Columbia University lattice group is also underway for a next generation RBRC lattice computer of about 200 teraflops sustained.

(2) Perturbative QCD and spin physics

The ongoing RHIC spin experiments have motivated much of the parallel theoretical developments at RBRC. In the area of transverse spin physics, novel predictions have been obtained for the single transverse-spin asymmetry in open charm production in pp collisions at RHIC. This asymmetry probes three gluon correlations in polarized proton. In addition, radiative QCD corrections to single-spin observables were investigated, providing the relevant evolution equations. Further work focused on hyperon production at RHIC, and on azimuthal asymmetries in the Drell-Yan process.

(3) Phenomenological QCD--QCD under extreme conditions--

To establish a detailed picture of relativistic heavy ion collisions, QCD-based theoretical approaches are in progress. Especially the idea of "color glass condensation (CGC)" can be a key to understand the initial condition of the heavy ion collision. Other phenomenological approaches are in progress to understand the characteristics of strongly interacting quark gluon plasma. A recent effort has been initiated to understand heavy ion elliptic flow in term s of viscous hydrodynamics. A new finite temperature effective field theory is being developed for the strongly interacting quark gluon plasma to explain the suppression of sheer viscosity in the region of the phase transition.

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RIKEN-BNL Research Center
Experimental Group

1. Abstract

RIKEN BNL Research Center (RBRC) Experimental Group studies the strong interactions (QCD) using RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized p+p collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment at RHIC. We study the spin structure of the proton using the polarized proton-proton collisions at RHIC. This program has been promoted by RIKEN's leadership. The first focus of the research is to measure the gluon spin contribution to the proton spin. Our recent data analysis has shown that the proton spin carried by the gluons is small, which is a very striking finding beyond our expectations. The aim of Heavy ion physics at RHIC is to re-create Quark Gluon Plasma, the state of Universe just after the Big Bang. Two important discoveries, jet quenching effect and strong elliptic flows, have established that new state of dense matter is indeed produced in heavy ion collisions at RHIC. We are proceeding to understand the nature of the matter. We has major roles in detector upgrades of PHENIX experiment, namely, the silicon vertex tracker (VTX) and muon trigger upgrades.

2. Major Research Subjects

(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) PHENIX detector upgrades

3. Summary of Research Activity

The RIKEN-BNL Research Center was established in 1997 to support the RIKEN activities at RHIC in BNL, and also to promote theoretical studies related to RHIC, i. e. theories of strong interaction. The center's first director was T. D. Lee (Columbia University), and in October 2003, the former director of BNL, N. P. Samios, succeeded to the post of the director. The center consists of a theory group lead by L. Mclerran (BNL) and an experimental group lead by Y. Akiba, a vice chief scientist of RIKEN in Wako.

We study the strong interactions (QCD) using the RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized p+p collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment.

(1) Experimental study of spin structure of proton using RHIC polarized proton collider

How is the spin of proton formed with 3 quarks and gluons? This is a very fundamental question in Quantum Chromodynamics (QCD), the theory of the strong nuclear forces. The RHIC Spin Project has been established as an international collaboration between RIKEN and Brookhaven National Laboratory (BNL) to solve this problem by colliding two polarized protons for the first time in history. This project also has extended the physics capabilities of RHIC.

The first goal of the RHIC spin physics program is to elucidate a contribution of the gluon spin in the proton spin. We have measured double-helicity asymmetries of neutral pions to study gluon polarization in proton. The most recent data from 2006 run have shown that the gluon polarization in the proton is small, and only about half of proton spin can be accounted by gluon spin in the measured region of gluon momentum in proton. The remaining part must be carried by gluons in lower momentum region where the measurement is not sensitive, and/or reside in the orbital-angular momentum of quarks and gluons.

To finalize the smallness of the gluon-spin contribution, we need to measure double helicitiy asymmetry in direct photon production. This process is dominated by a single and the simplest process, gluon Compton scattering, in perturbative QCD, and is the golden channel to determine the gluon density and the gluon polarization in the proton. We published a paper on direct photon cross section in p+p collisions at RHIC. Preliminary results on double-helicity asymmetry of direct photon from the 2006 run have been obtained.

We have also accumulating transversely-polarized proton collision data to measure single transverse-spin asymmetries of processes which are predicted to be sensitive to the orbital-angular momentum of quarks and gluons.

Since the RHIC operation in 2008 was shortened by the DOE budget problem there was a polarized-proton collisions for only about one-month long. The RHIC accelerator achieved $2.3 \times 10^{31}/cm^2/s$ of the average luminosity and 45% of the average beam polarization at the center-of-mass energy of 200 GeV. In 2008, we collected data with transversely-polarized proton collisions at 200 GeV to investigate single transverse-spin asymmetries. The PHENIX experiment recorded the data corresponding to 4.5 inverse picobarn of the integrated luminosity in 2008. All the physics data in the 2008 p+p run were transferred to RIKEN CC-J in almost real-time via the network between US and Japan. Event-reconstruction of the data has been completed at RIKEN CC-J.

In addition to the study of polarized p+p collisions at RHIC, we study quark fragmentation function. With collaboration with the BELLE experiment at High Energy Accelerator Research Organization (KEK), we discovered that the spin direction of a quark can be determined from its hadronic fragments. Precise data of the quark fragmentation function can be used to understand the cross sections and the spin dependences of particle production in polarized p+p collisions at RHIC. We continue the study of the quark fragmentation function at BELLE.

In 2009, we expect the first polarized p+p run at sqrt (s)=500 GeV. Main goal of the 500 GeV run is to measure single longitudinal spin asymmetry of W particle production. From this measurement, the polarization of the quarks and the anti-quarks in the proton can be determined.

(2) Experimental study of Quark-Gluon Plasma using RHIC heavy-ion collider

The goal of high energy heavy ion physics at RHIC is study of QCD in extreme conditions i. e. at very high temperature and at very high energy density. Experimental results from RHIC have established that dense partonic matter is formed in Au+Au collisions at RHIC. The matter is very dense and opaque, and it has almost no viscosity and behaves like a perfect fluid. These conclusions are primarily based on the following two discoveries:

●Strong suppression of high transverse momentum hadrons in central Au+Au collisions (jet quenching)
●Strong elliptic flow

The focus of the research in heavy ion physics at RHIC is now to investigate the properties of the matter. RBRC have played the leading roles in some of the most important results from PHENIX in the study of the matter properties.

From the fall of 2007 to the spring of 2008, RHIC had its 8th year RUN (RUN8). The first part of RUN8 was deuteron + gold (d+Au) collision experiment. PHENIX recorded very high statistics d+Au data during RUN8, about 30 times of the previous d+Au run in year 2003. From the d+Au data we can study the cold nuclear matter effect, in particular that on J/Psi production, a key probe of Quark Gluon plasma.

Main results of PHENIX that are published in 2008 are as follows.

1) Measurements of electron pairs in p+p.

Electron pairs are measured in p+p collisions at sqrt (s)=200 GeV. The measured mass distribution is well explained by the contribution of light meson decays for the mass region less than 1 GeV. The mass spectrum above 1 GeV is dominated by correlated decay of charm and anit-charm mesons. From the yield of the electron pair continuum above 1 GeV, the total charm production cross section is deduced. The obtained cross section is in good agreement with the measurement from single electrons.

2) J/Psi measurements in d+Au and Cu+Cu

Cold nuclear matter effects in J/PSI production in d+Au collisions are studied. The d+Au data were re-analyzed and compared with higher statistics p+p data. From the comparison, J/Psi break-up cross section in cold nuclear matter is determined. The final results of J/Psi production in Cu+Cu collision from year 2005 run of RHIC has been published.

3) High pT pi0 measurement and constraints on theory.

PHENIX measured pi0 production at high pT in Au+Au collision at 200 GeV. The new measurement has more than 10 times of statistics of the previous published results and extend the measured pT range to 20 GeV/c. The measurements shows that the pi0 production is strongly suppressed, by about a factor of five, at high pT. The suppression is consistent with that high pT scattered quarks and gluons lose a significant amount of their energies in the dense matter formed in the collision. The suppression patterns are compared with the theory calculations of parton energy loss. Form the comparison, quantitative constraints on the parameters of the theories are obtained.

4) Measurement of low pT direct photons through their internal conversion to e+e- pairs.

If the dense partonic matter formed at RHIC is thermalized, it should emit thermal photons. Observation of thermal photon is direct evidence of early thermalization, and we can determine the initial temperature of the matter. It is predicted that thermal photons from QGP phase is the dominant source of direct photons for 1<pT<3 GeV/c at the RHIC energy. PHENIX measured the direct photon in this pT region from measurements of quasi-real virtual photons that decays into low-mass e+e- pairs. Strong enhancement of direct photon yield in Au+Au over the scaled p+p data has been observed. Several hydrodynamical models can reproduce the central Au+A data within a factor of two. These models assume formation of a hot system with initial temperature of Tinit=300 MeV to 600 MeV.

(3) PHENIX detector upgrade

The group has major roles in several PHENIX detector upgrades, namely, the silicon vertex tracker (VTX) and muon trigger upgrades.

VTX is 4 layers of silicon tracker, jointly funded by RIKEN and the US DOE. The inner two layers are silicon pixel detectors and the outer two layers are silicon strip detectors. The detector will be completed in 2010.

Muon trigger upgrades are needed for W → mu measurement at 500 GeV. New trigger electronics (Muon Trigger FEE) have been installed in one of muon arms and they will be commissioned in the 2009 run. After the 2009 run, the rest of the Muon Trigger FEE will be installed in PHENIX. Prototype of muon trigger detectors using MRPC technology have been installed for test during the 2009 run.

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Center for Nuclear Study, Graduate School of Science, University of Tokyo.

1. Abstract

The Center for Nuclear Study (CNS) aims to elucidate the nature of nuclear system by producing the characteristic states where the Isospin, Spin and Quark degrees of freedom play central roles. These researches in CNS lead to the understanding of the matter based on common natures of many-body systems in various phases. We also aim at elucidating the explosion phenomena and the evolution of the universe by the direct measurements simulating nuclear reactions in the universe. In order to advance the nuclear science with heavy-ion reactions, we develop AVF upgrade, CRIB and SHARAQ facilities in the large-scale accelerators laboratories RIBF. We promote collaboration programs at RIBF as well as RHIC-PHENIX and ALICE-LHC with scientists in the world, and host international meetings and conferences. We also provide educational opportunities to young scientists in the heavy-ion science through the graduate course as a member of the department of physics in the University of Tokyo and through hosting the international summer school.

2. Major Research Subjects

   (1) Accelerator Physics
   (2) Nuclear Astrophysics
   (3) Nuclear spectroscopy of exotic nuclei
   (4) Quark physics
   (5) Spin Physics
   (6) Nuclear Theory
   (7) SHARAQ project

3. Summary of Research Activity

(1)   Accelerator Physics

   One of the Major tasks of the accelerator group is the AVF upgrade project which includes development of ion sources, upgrading the AVF cyclotron of RIKEN and the beam line to CRIB. A new heavy ion ECR source of CNS that use super-conducting magnet was successfully installed to the AVF cyclotron, and has been used to provide a variety heavy ion beams. Two CNS ECR sources now provide all the beams for the AVF cyclotron and support not only CRIB experiments but also a large number of RIBF experiments. A charge-breeding ECR source is also under development.

   Two major works were advanced for upgrading the AVF cyclotron. One is the detailed design study of the central region of the cyclotron, which remedies insufficiencies for the transmission of the heavy ion beams through the cyclotron. A new central module will be made following the design in 2009. The second is a successful acceleration of heavy ion beams up to 11 Mev/u which was about 9.5 MeV/u before. Following the detailed simulation studies of the heavy ion beams through the cyclotron, beam acceleration tests were successfully performed for ^{16}O and ^{6}Li beams. These beams will be provided to new experimental projects at CRIB.

   A non-destructive beam monitor was also successfully developed and installed just in front of the CRIB production target. It showed a sensitivity of about a few nA. This new beam monitor will become a powerful tool for all the RIBF facility.

(2)   Nuclear Astrophysics

   Major activity of the nuclear astrophysics group is to investigate experimentally nucleosynthesis of the universe, specifically of explosive phenomena in the universe such as novae and supernovae. High-intensity RI beams of light nuclei from the CNS low-energy RI beam separator CRIB provides a good opportunity to study stellar nuclear reactions under explosive conditions both by the direct method as well as by indirect methods. The research programs include investigations of α-induced stellar reactions on ^{7}Li, ^{14}O and ^{21}Na.

The beta decay of ^{46}Cr was also studied to learn the Gamow-Teller Transitions. Some beam developments were made for new RI beams, and an active target was also designed for studies of stellar reactions with low-cross sections.

Some technological development for the beam line as well as for the Wienfilter of CRIB were made in the past year.

(3) Nuclear structure of exotic nuclei

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) group studies exotic structures in high-isospin and/or high-spin states in nuclei. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is a major apparatus for high-resolution in-beam gamma-ray spectroscopy. In 2008, the following progress has been made.

Light neutron-rich nuclei have been studied by using nucleon transfer and inelastic scattering where the final states are identified by measuring de-excited gamma-rays. A low-lying proton intruder state has been found for the first time, which shows importance of a deformation effect in N ~ 8 neutron-rich nuclei.

New high-spin states in $^{49-51}$Ti populated by fusion reactions of an RI beam have been found, which gives information on the N=28 shell gap and the single particle energies in the fp-shell.

Upgrade of the readout system of the CNS GRAPE has started, where digital pulse data taken by sampling ADCs are analyzed by FPGAs on boards.

(4) Quark Physics

Main goal of the CNS quark physics group is to understand the properties of hot and dense nuclear matter created by colliding heavy nuclei at relativistic energies. The group has been involved in the PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) at Brookhaven

National Laboratory, and has also started active participation in the ALICE experiment at Large Hadron Collider (LHC) at CERN.

As for the RHIC PHENIX experiment, the group has been concentrating on the physics analysis with leptons and photons, which include study of charm and bottom production with the non-photonic single electrons, measurement of direct photon yield at low transverse momentum in p+p and A+A collisions using the virtual-gamma method, and determination of neutral pion yield as a function of azimuthal angle from the reaction plane in Au+Au collisions.

As for the LHC ALICE experiment, the group has been playing roles in the construction of the Transition Radiation Detector (TRD), and commissioning and calibration of Time Projection Chamber (TPC).

R&D of gas electron multiplier (GEM) and related techniques has been continuing. The major activities are; development of 2D-imaging prototype, and performance study of the thick-GEM prototypes with several different hole sizes.

(5) Spin Physics

Development of the polarized solid proton target is being proceeded. We have examined how the proton polarization rate depends on pulse structure of excitation light and found that the polarization rate can be doubled for a duty factor of 20% and a repetition rate of 7.5 kHz, compared with the previous settings of 5% and 2.5 kHz. Higher proton polarization can be expected with this new settings.

(6) Nuclear Theory

The nuclear theory group has been promoting the RIKEN-CNS collaboration project on large-scale nuclear structure calculations since 2001 and maintaining its parallel computing cluster. In 2008, we developed the effective interactions of various mass region based on the large-scale shell model calculation technique and discussed the "shell evolution" and the role of tensor force quantitatively in exotic nuclei, such as ^{17}C, ^{48}Ca, N=50 isotones, Sm isotopes and so on.

(7) SHARAQ project

Construction of the SHARAQ spectrometer and the dedicated high-resolution beamline are coming to the final phase. The magnetic field distribution in dipole magnets, D1 and D2, were precisely measured with the search coil method. A major part of the beamline has been constructed. Cathode readout drift chambers for

tracking detectors at the SHARAQ focal plane have been fabricated in GANIL and installed to SHARAQ in December 2008. It was also found that Low-pressure multiwire drift chambers (LP-MWDC) developed for beamline tracking detectors works well under pressure as low as 10 kPa with an isobuthane gas.

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TORIJIN
(Todai-RIKEN Joint International Program for Nuclear Physics) Term

1. Abstract

University of Tokyo and RIKEN agreed to corporate with each other in the field of nuclear physics and established Todai-RIKEN Joint International Program for Nuclear Physics (TORIJIN) in June 2006. The aim of this organization is to promote the international collaborations, such as JUSTIPEN (Japan-US Theory Institute for Physics with Exotic Nuclei) and EFES (International Research Network for Exotic Femto Systems). JUSTIPEN was launched in June 2006 in order to facilitate collaborations between U. S. and Japanese scientists whose main research thrust is in the area of the physics of exotic nuclei. More than 40 nuclear scientists in U. S. have visited Japan in three years, and many collaborations are established. EFES was selected as one of the Core-to-Core Programs of Japan Society for the Promotion of Science (JSPS). This is the program to send Japanese nuclear scientists to U. S., Germany, France, Italy, Norway, and Finland and to promote the international collaborations in the field of nuclear study. Many joint workshops were held with the partner countries.

2. Main activities

Promote the international collaborations of both theoretical and experimental nuclear physicists under JUSTIPEN and EFES programs.

3. Summary of Research Activity

Under the JUSTIPEN program, 26 nuclear scientists visited in this fiscal year and many collaborations are established. Under the EFES program, we have carried out four types of activities: initiating the collaboration projects, organizing seminars with partner courtiers, sending researchers abroad, and sending/inviting young scientists to the summer schools. Regarding the collaborative works, we have carried out three projects. Many experimentalists and theoreticians have been sent abroad. As for the joint workshops, we have organized eight workshops and all of them were quite fruitful. Also, young scientists have been sent to partner countries for educational purpose and starting collaborations. As for the summer school, Japanese graduate students have been sent to the summer schools in Germany and USA, and we have invited students to CNS-EFES summer school from the partner countries.

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VI. LIST OF PUBLICATIONS

& PRESENTATION

Accelerator Division

Publications

[Journal]

(Original Papers)　*Subject to Peer Review

Aoki T., Stingelin L., Kamigaito O., Sakamoto N., Fukunishi N., Yokouchi S., Maie T., Kase M., Goto A., and Yano Y.: "Construction of a beam rebuncher for RIKEN RI-beam factory", Nucl. Instrum. Methods Phys. Res. A **592**, No. 3, pp. 171–179 (2008). *

[Book・Proceedings]

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(Others)

Okuno H., Fukunishi N., Fujinawa T., Goto A., Higurashi Y., Ikezawa E., Kamigaito O., Kase M., Nakagawa T., Ohnishi J., Sato Y., Yano Y., and Ostroumov P.: "Heavy Ion Accelerators for RIKEN RI Beam Factory and Upgrade Plans", 42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams, Nashville, USA, 2008–8, ICFA, , p. (2009).

Oral Presentations

(International Conference etc.)

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GARIS Team

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BigRIPS Team

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Oral Presentations

(International Conference etc.)

N. Itagaki, " Multi cluster correlations studied with UCOM-like treatment", First EMMI-EFES workshop on neutron-rich exotic nuclei "Realistic effective nuclear forces for neutron-rich nuclei" 9-11 Feb., GSI, Germany

N. Itagaki, "Cluster-like correlations in light nuclei", The 3rd LACM-EFES-JUSTIPEN workshop, 23-25 Feb., Oak Ridge National Lab., USA

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VII. LIST OF PREPRINTS

1. Y. Satou, T. Nakamura, N. Fukuda, T. Sugimoto, Y. Kondo, N. Matsui, Y. Hashimoto, T. Nakabayashi, T. Okumura, M. Shinohara, T. Motobayashi, Y. Yanagisawa, N. Aoi, S. Takeuchi, T. Gomi, Y. Togano, S. Kawai, H. Sakurai, H. J. Ong, T. K. Onishi, S. Shimoura, M. Tamaki, T. Kobayashi, H. Otsu, Y. Matsuda, N. Endo, M. Kitayama, and M. Ishihara : " Unbound excited states in 19,17C "

2. M. Yamagami, and Y. R. Shimizu : " Spatial structure of neutron Cooper pairs in deformed neutron-rich nuclei "

3. A. Kohama, K. Iida, and K. Oyamatsu : " Difference between interaction cross sections and reaction cross sections "

4. T. Ohnishi, T. Kubo, K. Kusaka, A. Yoshida, K. Yoshida, N. Fukuda, M. Ohtake, Y. Yanagisawa, H. Takeda, D. Kameda, Y. Yamaguchi, N. Aoi, K. Yoneda, H. Otsu, S. Takeuchi, T. Sugimoto, Y. Kondo, H. Scheit, Y. Gono, H. Sakurai, T. Motobayashi, H. Suzuki, T. Nakao, H. Kimura, Y. Mizoi, M. Matsushita, K. Ieki, T. Kuboki, T. Yamaguchi, T. Suzuki, A. Ozawa,. T. Moriguchi, Y. Yasuda, T. Nakamura, T. Nannichi, T. sumikama, Y. Nakayama, H. Geissel, H. Weick, J. A. Nolen, O. B. Tarasov, A. S. Nettleton, D. P. Bazin, B. M. Sherrill, D. J. Morrissey, and W. Mittig : " Identification of New Isotopes 125Pd and 126Pd produced by In-flight Fissiion of 345 MeV/nucleon 238U: First Results from the RIKEN RI Beam Factory "

5. N. Iwasa, T. Motobayashi, S. Bishop, Z. Elekes, J. Gibelin, M. Hosoi, K. Ieki, K. Ishikawa, H. Iwasaki, S. Kawai, S. Kubono, K. Kurita, M. Kurokawa, N. Matsui, T. Minemura, H. Morikawa, T. Nakamura, M. Niikura, M. Notani, S. Ota, A. Saito, H. Sakurai, S. Shimoura, K. Sugawara, T. Sugimoto, H. Suzuki, T. Suzuki, I. Tanihata, E. Takeshita, T. Teranishi, Y. Togano, K. Yamada, K. Yamaguchi, and Y. Yanagisawa : " Large proton contribution to the 2+ excitation in 20Mg studied by intermediate energy inelastic scattering "

6. D. Suzuki, H. Iwasaki, H. J. Ong, N. Imai, H. Sakurai, T. Nakao, N. Aoi, H. Baba, S. Bishop, Y. Ichikawa, M. Ishihara, Y. Kondo, T. Kubo, K. Kurita, T. Motobayashhi, T. Nakamura, T. Okumura, T. K. Onishi, S. Ota, M. K. Suzuki, S. Takeuchi, Y. Togano, and Y. Yanagisawa: "Lofetime measurements of excited states in 17C : possible interplay between collectivity and halo effects "

7. S. Ota, S. Shimoura, H. Iwasaki, M. Kurokawa, S. Michimasa, N. Aoi, H. Baba, K. Demichi, Z. Elekes, T. Fukuchi, T. Gomi, S. Kanno, S. Kubono, K. Kurita, H. Haseggawa, E. Ideguchi, N. Iwasa, Y. U. Matsuyama, K. L. Yurkewicz, T. Minemura, T. Motobayashi, T. Murakami, M. Notani, A. Odahara, A. Saito, H. Sakurai, E. Takeshita, S. Takeuchi, M. Tamaki, T. Teranishi, Y. Yanagisawa, K. Yamada, and M. Ishihara : " Low-Iying Proton Intruder State in 13B "

8. Z. Elekes, N. Aoi, Zs. Dombrädi, Zu. Fülöp, T. Motobayashi, and H. Sakurai : " Inelastic Scattering studies of 16C revisited "

9. M. Ito, N. Itagaki, H. Sakurai, and K. Ikeda : " Coexistence of covalent superdeformation and molecular resonances in an unbound region of 12Be "

10. M. Ito and N. Itagaki : " Covalent isomeric state in 12Be induced by two-neutron transfers "

11. M. Yamagami, and Y. R. Shimizu, and T. Nakatsukasa : " Optimal pair density functional for description of nuclei with large neutron excess "

12. J. Gibelin, D. Beaumel, T. Motobayashi, Y. Blumenfeld, N. Aoi, H. Baba, Z. Elekes, S. Fortier, N. Frascaria, N. Fukuda, T. Gomi, K. Ishikawa, Y. Kondo, T. Kudo, V. Lima, T. Nakamura, A. Saito, Y. Satou, J. -A. Scarpaci, E.Takeshita, S. Takeuchi, T. Teranishi, Y. Togano, A. M. Vinodkumar, Y. Yanagisawa, and K. Yoshida : "Decay Pattern of Pygmy States Observed in neutron-Rich 26Ne "

13. T. Suda, M. Wakasugi, T. Emoto, K. Ishii, S. Ito, K. Kurita, A. Kuwajima, A. Noda, T. Shirai, T. Tamae, H. Tongu, S. Wang, and Y. Yano : " First Demonstration of Electron Scattering using a Novel Target Developed for Short-Lived Niclei "

14. N. Imai, N. Aoi, H. J. Ong, H. Sakurai, K. Demich, H. Kawasaki, H. Baba, Zs. Dombradi, Z. Elekes, N. Fukuda, Zs. Fulop, A. Gelberg, T. Gomi, H. Hasegawa, K. Ishikawa, M. Ishihara, H. Iwasaki, E. Kaneko, S. Kanno, T. Kishida, Y. Kondo, T. Kubo, K. Kurita, S. Michimasa, T. Minemura, M. Miura, T. Motobayashi, T. Nakamura, M. Notani, T. K. Ohnishi, A. Saito, S. Shimoura, T. Sugimoto, M. K. Suzuki, E. Takeshita, S. Takeuchi, M. Tamaki, H. Watanabe, and K. Yoneda : " First lifetime measurement of 2+1 state in 12Be "

RIKEN- NC- AC
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1. T. Fujisawa: " Impedance Matching in Radio-Frequency Circuits "

CNS-REP

1. S.Ota, S.Shimoura, H.Iwasaki, M.Kurokawa, S.Michimasa, N.Aoi, H.Baba, K.Demichi, Z.Elekes, T.Fukuchi, T.Gomi, S.Kanno, S.Kubono, K.Kurita, H.Hasegawa, E.Ideguchi, N.Iwasa, Y.U.Matsuyama, K.L.Yurkewicz, T.Minemura, T.Motobayashi, T.Murakami, M.Notani, A.Odahara, A.Saito, H.Sakurai, E.Takeshita, S.Takeuchi, M.Tamaki, T.Teranishi, Y.Yanagisawa, K.Yamada, and M.Ishihara:
"Low-lying Proton Intruder State in ^{13}B"

2. H.Yamaguchi, Y.Wakabayashi, S.Kubono, G.Amadio, H.Fujikawa, T.Teranishi, A.Saito, J.J.He, S.Nishimura, Y.Togano, Y.K.Kwon, M.Niikura, NIwasa, K.Inafuku, and L.H.Khirm:
"Low-lying non-normal parity states in ^{8}B measured by proton elastic scattering on ^{7}Be"

VIII. LIST OF SYMPOSIA

（2008 Apr. ～ 2009 Mar.）

1. SAKURA Workshop "International Workshop on Materials and Life Science using Nuclear Probes from High-energy Accelerators" 1-3 Apr. Advanced Meson Science Laboratory

2. CNS-RIKEN Joint International Symposium on Frontier of gamma-ray spectroscopy and Perspectives for Nuclear Structure Studies (gamma08)" 3-5 Apr. CNS,Univ.Tokyo, & RIKEN

3. RIKEN Workshop "Mutation breeding for microorganisms using heavy ion beams" 8 Apr. Radiation Biology Team RIKEN & KEK

4. Riken BNL Workshop "Hydrodynamics in Heavy Ion Collisions and QCD equation of state" 21-22 Apr. RBRC

5. Riken BNL Workshop "Understanding QGP through spectral functions and Euclidean Correlators" 23-25 Apr. RBRC

6. Brookhaven Symposium "Neutrino Helicity at 50: A Celebration of the Goldhaber-Grodzins-Sunyar Experiment" RBRC

7. Workshop "Plant biotechnology for flower breeding in Thailand" 21 May Radiation Biology Team RIKEN

8. Workshop "Mutation breeding for salt tolerant rice" 9 Jun. Radiation Biology Team RIKEN

9. The Frontier of Isotope Science (from nuclear physics to nuclear medicine) 1 Jul. RIKEN & JRIA

10. Joint Illinois-MIT-RBRC Workshop on "Gluon Polarization in the Nucleon" in Urbana 16-17 Jun. RBRC

11. PKU-RBRC Workshop on "Transverse Spin Physics" in Beijing　30 Jun. RBRC

12. Hokudai-TORIJIN JUSTIPEN-EFES workshop "Perspective in Resonances and Continua on nuclei & JUSTIPEN-EFES-Hokkaido-UNEDF meeting", 21-25 July, Onuma, Hokkaido, EFES, TORIJIN, JUSTIPEN, Hokkaido University

13. Spin Fest lectures August 4-5, Introduction to pQCD by George Sterman (Stony Brook) August 6-7, Transverse Spin Structure of the Nucleon by Mauro Anselmino (Torino) August 7, Acceleration of Polarized Protons by Mei Bai (BNL) August 8, Nucleon Structure and Lattice QCD by John Negele　（MIT）RBRC

14. Workshop on the future of hadron physics at J-PARC 1-2 Sep. Strangeness Nuclear Physics Laboratory & Advanced Meson Science Laboratory RIKEN

15. STAR Workshop "Workshop on the Ridge" 22-24 Sep.　RBRC

16. 1st JaFNA Workshop on Research Strategy: Program "New Era of Nuclear Physics in the Cosmos -the r-process nucleosynthesis" 25-26 Sep.

17. Japanese-French Symposium "New Paradigms in Nuclear Physics", 29 Sep. – 2 Oct., Paris, France, EFES, CNRS, IN2P3, RIKEN, IPN, GANIL

18. RSC meeting in Stony Brook 3 Oct. RBRC

19. Special Stony Brook Workshop "Celebration of Edward Shuryak's 60th Birthday" 2-3 Oct.

RBRC

20. ATHIC2008 TSUKUBA 13-15 Oct. CCS,Univ.Tsukuba & RIKEN Nihsina Center& CNS,Univ.Tokyo

21. BNL Workshop " UDiG workshop" 16-17 Oct. RBRC

22. International Symposium on New Facet of Spin-Isospin Responses 〜 Toward the Commissioning of SHARAQ Spectrometer 〜 29 Oct. CNS,Univ.Tokyo & RIKEN

23. ICHOR-EFES International Symposium on New Facet of Spin-Isospin Responses, 29-31 Oct., Wako, RIKEN, ICHOR program, EFES, RIKEN, CNS University of Tokyo

24. Special High Energy Workshop "Terra Incognita: From LHC to Cosmology" 6-8 Nov. RBRC

25. The 6th Japan-Italy symposium on Heavy Ion Physics, 11-15 Nov., Tokai, JAEA, KEK, RIKEN, NAO, CNS University of Tokyo, EFES

26. Workshop on Superheavy Element Chemistry 2008 12 Nov. Superheavy Element Laboratory RIKEN

27. Special BNL Workshop "Symposium for Gerry Bunce: Celebrating 32 Years of Spin Physics Research at Brookhaven" 19 Nov. RBRC

28. Workshop on Giant Resonances with Inverse Kinematics and Missing Mass Techniques 25 Nov. Nuclear Physics Research Division RIKEN

29. Workshop on Future perspectives in nuclear physics 26-27 Nov. Strangeness Nuclear Physics Laboratory & Theoretical Nuclear Physics Laboratory RIKEN

30. Joint ANL-EFES Workshop for a Compton-Suppressed Ge Clover Array for Stopped and Energy Degraeded Exotic Beams at RIKEN, 4-5 Dec., Argonne National Lab., USA, EFES, Argonne National Lab.

31. Workshop on the recent progress and future of physics on few-body problem 23-25 Dec. Strangeness Nuclear Physics Laboratory RIKEN

32. RIKEN Workshop " The use of ion beam for mutation induction in plants and animal cells" 9 Jan. Radiation Biology Team RIKEN & The Wakasa Wan Energy Research Center

33. A Planning of Synchrotron X-ray Use of RIBF at Wako RIKEN 13 Jan. Nishina Center RIKEN

34. Workshop " The use of ion beam for mutation induction in plants and microorganisms" 28 Jan. Radiation Biology Team RIKEN

35. First EMMI-EFES workshop on neutron-rich exotic nuclei "Realistic effective nuclear forces for neutron-rich nuclei" 9-11 Feb., GSI, Germany, EMMI, GSI, EFES

36. Workshop on Competition of hydrogen burning with vp-process and r-process in explosive nucleosynthesis, 19-20 Feb.,Nishina Hall, RIKEN, CNS University of Tokyo, RIKEN, JSPS.

37. The 3rd LACM-EFES-JUSTIPEN workshop, 23-25 Feb., Oak Ridge National Lab., USA, EFES, JUSTIPEN, Oak Ridge National Lab.

38. CATHIE-RIKEN Workshop "Critical Assessment of Theory and Experiment on Correlations

at RHIC " 25-26 Feb. RBRC

39.　Workshop on the study of hypernuclear physics and neutron star 1 Mar. Strangeness Nuclear Physics Laboratory RIKEN

40.　Fist LIA-EFES workshop "Low-energy collective motion of exotic nuclei", 2-4 Mar., GANIL, France, LIA, EFES, GANIL

41.　Joint Theory/Experimental Workshop "Early Physics at the LHC " 16 Mar. RBRC

IX. LIST OF SEMINAR

(2008 Aplr. ~ 2009 Mar.)

Accelerator Division

1　Jacques Cherix （PSI）16 Apr.「PSI National Research Center in Switzerland」

2　Jacques Cherix （PSI）16 Apr.「The RF of the PSI Cyclotron, Specifically LLRF」

3　Jameson （BNL）23 May「Discussion on Comparison of Design and Simulation Codes for RFQs」

4　H. Sakaki （Japan Atomic Energy Agency）11 Jun.「Statistical analysis and control of beam energy for electron linear accelerator」

5　T. Shirai （National Institute of Radiological Sciences）25 Jul.「Ultra Cold Ion Beam Experiments by Electron and Laser Cooling at Ion Storage Ring, S-LSR」

6　I. Yamane （KEK）23 Jan.「Magnetic Neutralizer for cw beam-splitting of high energy H-beam and possibility of Laser Neutralizer option」

7　P. Ostroumov （Argonne National Laboratory）3 Mar.「Development of superconducting heavy-ion accelerators at ANL」

8　F. Marti （MSU）6 Mar.「From NSCL to FRIB, challenges and opportunities.」

9　I. Sugai （KEK）6 Mar.「Development of hybrid long-lived carbon foils with high heat resistance even at 1800 K」

10　N. Nakamura （ILS）13 Mar.「Principle and application of an electron beam ion source/trap (EBIS/T)」

Nuclear Physics Research Division

1　S. G. Frauendorf （Research Center Dresden-Rossendorfand Univ. of Notre Dame）8 Apr. RIBF Nuclear Physics Seminar「Dynamic and static chirality of rotating triaxial nuclei」

2　Y. Nagai （Japan Atomic Energy Agency）15 Apr. Monthly Colloquium 「Nuclear Astrophysics studied with neutron, alpha, and gamma-ray」

3　M. Oi （Physics Department, University of Surrey）23 Apr. RIBF Nuclear Physics Seminar「Superdeformation of 40Ca」

4　A. Schwenk （TRIUMF）25 Apr. RIBF Nuclear Physics Seminar「Frontiers in understanding matter at the extremes」

5　H. Murayama （IPMU, Tokyo University）13 May Monthly Colloquium「The Next Twenty Years in Particle Physics」

6　S. Shimoura （CNS, Univ. of Tokyo）27 May Lecture Series IV-1「Practical nuclear reaction theory for experimentalists (3rd)」

7　T. Nakatsukasa （RIKEN Nishina Center）10 Jun. RIBF Nuclear Physics Seminar「Nuclear structure studied with the Skyrme density functional approach」

8　H. Toki （RCNP, Osaka University）17 Jun. Monthly Colloquium「Tensor optimized shell model and role of pion in nuclear physics」

9　P. Doornenbal （RIKEN Nishina Center）24 Jun. RIBF Nuclear Physics Seminar「Probing nuclear structure far-off stability with RISING-Gamma-ray spectroscopy with Radioactive Beams at GSI」

10　K. Nakai （KEK）2 Jul. RIBF Nuclear Physics Seminar「UNclear physics to NUclear physics」

11　T. Nishio （Research Center for Innovative Oncology, National Cancer Center）15 Jul. Monthly Colloquium「Imaging of the irradiated volume using positron-emigttingnuclei generated in a patient body by the target nuclear fragment reaction for proton therapy」

12　P. Avogadro （RIKEN Nishina Center）16 Jul. RIBF Nuclear Physics Seminar「Vortices and nuclei in the inner crust of a neutron star」

13　M. Takashina （RCNP, Osaka University）, *el al* 16 Jul. RIBF Mini-workshop「Analysis of inelastic proton scattering on unstable nuclei using single-folding model with JLM potential」

14　M. Yamagami, *el al* 3 Sep. RIBF Mini-workshop「Probing dineutron correlations in RIBF experiment」

15　S. Bishop （Technische Universitaet Muenchen）21 Oct. RIBF Nuclear Physics Seminar「Elastic Scattering of 7Be, 8B and a Roadmap to a Self-Consistent Approach to the 7Be (p, gamma) Solar S-Factor」

16　M. Takechi （RIKEN Nishina Center）28 Oct. RIBF Nuclear Physics Seminar「Study of Total Reaction Cross Sections

at Intermediate Energies」

17　M. Kamimura　(RIKEN Nishina Center)　6 Nov. Monthly Colloquium「Big-bang nucleosysnthesis reactions catalyzed by SUSY particle stau.」

18　K. Langanke　(GSI)　17 Nov. Lecture Series VII-1「Nuclear Astrophysics (1st)」

19　A. Masaike　(Kyoto University)　9 Dec. Monthly Colloquium「Perspective of High Energy Physics, Challenge in US and Japan」

20　Z. Fulop　(ATOMKI)　16 Dec. RIBF Nuclear Physics Seminar「Cross section data for the astrophysical p-process」

21　Betty Tsang　(NSCL, Michigan State University)　and 8 other authors 16-17 Dec. Mini-workshop「Nuclear Collisions and Nuclear Matter」

22　P. Moller　(Theoretical Division, Los Alamos National Laboratory)　19 Dec. RIBF Nuclear Physics Seminar「FISSION AT THE END OF THE NUCLEAR CHART」

23　A. N. Andreyev　(IKS, KU Leuven, Belgium)　19 Dec. RIBF Nuclear Physics Seminar「Electron-capture delayed fission (ECDF) in the lead region」

24　I. Hamamoto　(Lund University)　24 Dec. Lecture Series V-3「One-particle motion in nuclear many-body problem」

25　Ma. Hori　(Group leader, Max Planck Institute of Quantum Optics)　8 Jan. RIBF Nuclear Physics Seminar「High precision spectroscopy of antiprotonicatoms-new techniques to manipulate antimatter.」

26　H. Oigawa　(Japan Atomic Energy Agency)　22 Jan. Monthly Colloquium「Nuclear transmutation technology for ? long-lived radioactive nuclides」

27　M. Wada　(RIKEN NishinaCenter)　29 Jan. RIBF Nuclear Physics Seminar「Precision optical spectroscopy of Be isotopes」

28　M. Lantz　(RIKEN Nishina Center)　17 Feb. RIBF Nuclear Physics Seminar「FLUKA - A Monte Carlo code for physics and applications」

29　M. Ito　(RIKEN NishinaCenter)　17 Feb. RIBF Nuclear Physics Seminar「Unified studies of structures and reactions in light neutron-rich nuclei---Present analysis of 10,12Be and future perspectives---」

30　M. Schadel　(GSI)　2 Mar. RIBF Nuclear Physics Seminar「Superheavy element research at GSI」

31　K. Muto　(TITECH), *el al* 18-19 Mar.「Explorative investigation for the measurement of Gamow-Teller transition strength for neutron rich nuclei」

32　S. Chiba　(JAEA), *el al* 25-26 Mar. Mini-workshop「Nuclear data and nuclear theory」

Theoretical Nuclear PhysicsLaboratory

1　Y. M. Zhao　(Shanghai Jiao Tong Univ.)　21 May 7th Nuclear Theory Seminar「Approximate approach of obtaining eigenvalues of given matrices」

2　L. Guo　(Univ. Tokyo)　11 Jun. 8th Nuclear Theory Seminar「Boost-invariant TDHF theory and the nuclear Landau-Zener effect」

3　Y. Iwata　(Univ. Tokyo)　9 Jul. 9th Nuclear Theory Seminar「Reduced charge equilibration in heavy-ion collision at higher energy and synthesis of neutron-rich nuclei」

4　G. Watanabe　(Univ. Trento)　6 Aug. 10th Nuclear Theory Seminar「Nuclear pasta phases in supernovae and neutron stars: Qquantum molecular dynamics approach and future prospects」

5　H. Schulz　(INFN, Universita di Catania)　7 Jan. 11th Nuclear Theory Seminar "Pairing Gaps in Neutron Star Matter"

6　W. Long　(Peking University and Technischen Universitat Munchen)　18 Feb. 12th Nuclear Theory Seminar「Relativistic Hartree-Fock-Bogoliubov theory with Density Dependent Meson-Nucleon Couplings」

Radiation Laboratory

1　Dr. O. Sasaki　(KEK Associate Professor)　15 May Experience for development and construction of ATLAS TGC

readout

2 Prof. Freieder lenz (TheUniv. Erlangen-Nurnberg), *el al* 13 Nov. Lab. Seminar Physics Discussions with Frieder Lenz

Advanced Meson Science Laboratory

1 M. Iwasaki (Graduate School of Science, University of Tokyo) 25 Jun. Lab. Seminar「Study of B-meson rare decays at the Belle experiment」

2 K. Ohishi (RIKEN Nishina Center) 27 Aug. Lab. Seminar「Influence of self-irradiation in superconducting PuCoGa5 probed by uSR」

3 Risdiana (RIKEN Nishina Center) 27 Aug. Lab. Seminar「μSR study of Cu-Spin Fluctuations in Hole and Electron-Doped High-Tc Superconducting Cuprates」

4 M. Arai (Materials and Life Science Division, J-PARC) 21 Jan. Lab. Seminar「Neutron scattering approach on strongly correlated electron systems」

5 K. Hashimoto (RIKEN Nishina Center) 19 Mar. Lab. Seminar「Superstring theory」

Theoretical Physics Laboratory

1 Y. Tachikawa (School of Natural Sciences, Institute for Advanced Study, USA) 4 Apr. RIKEN Seminar「New Developments in d=4, N=2 Superconformal Field Theory」

2 F. Nori (Digital Materials Lab.) 14 Apr. Colloquium「Quantum Circuits as Artificial Atoms」

3 A. Tsuchiya (Shizuoka University) 18 Apr. RIKEN Seminar「Fiber Bundles and Matrix Models」

4 S. Matuura (Niels Bohr Institute, Danmark) 25 Apr. RIKEN Seminar「Relation among supersymmetric lattice gauge theories and matrix theories」

5 Y. Matsuo (Department of Physics, Faculty of Science, University of Tokyo) 27 May RIKEN Seminar「Lie 3-algebra and multiple M2 branes」

6 D. Yamada (Racah Institute of Physics, The Hebrew University of Jerusalem, Israel) 10 Jun. RIKEN Seminar「Phase Diagrams of N=4 SYM in Strong and Weak Couplings」

7 C. Albertsson (Yukawa Institute for Theoretical Physics, Kyoto University) 17 Jun. RIKEN Seminar「D-branes in doubled geometry」

8 K. Hashimoto (RIKEN Nishina Center) 18 Jun. Colloquium「The Frontiers of Superstring Theory : "D-branes" and new perspective of our world」

9 M. Passera (INFN) 27 Jun. RIKEN Seminar「The muon g-2 and the bounds on the Higgs boson mass」

10 N. Maru (Department of Physics, Kobe University) 8 Jul. RIKEN Seminar「Direct Gauge Mediation of Metastable Supersymmetry Breaking」

11 Y. Koichi (Graduate School of Science, Kyoto University) 15 Jul. RIKEN Seminar「Detection of neutrino from extra dimensions」

12 N. Jokela (Helsinki Institute of Physics, Finland) 22 Jul. RIKEN Seminar「Rolling tachyons, random matrices, and Coulomb gas thermodynamics」

13 A. D'adda (I. N. F. N. Sezione di Torino, Italy) 29 Sep. "New Era of Nuclear Physics in the Cosmos -the r-process nucleosynthesis"

14 W. Vinci (University of Pisa) 6 Oct. RIKEN Seminar「New Developments on Non-Abelian Vortices」

15 H. Kawai (RIKEN Nishina Center) 17 Oct.「Seminar to introduce the Nobel prize in physics 2008 for novices」

16 Y. Sugita (Theoretical Biochemistry Laboratory) 20 Oct. Colloquium「All-atom molecular dynamics simulations of membrane proteins in lipid bilayer」

17 T. Yamashita (E-ken, Theoretical Particle Physics Group Department of Physics, Graduate School of Science Nagoya University) 20 Oct. RIKEN Seminar「Gauge-Higgs Dark Matter」

18 Prof. Deog-Ki Hong (Department of Physics, Pusan National University, Korea) 20 Oct. RIKEN Seminar「Holographic QCD and Baryons」

19 T. Onogi (Yukawa Institute for Theoretical Physics, Kyoto University) 1 Nov. RIKEN Seminar「Lattice study of the conformal window in QCD with many flavors」

20 J. Nishimura (KEK) 1 Nov. RIKEN Seminar「Simulating Superstrings inside a Black Hole」

21 A. Tsuchiya (Department of Physics, Shizuoka University) 1 Nov. RIKEN Seminar「N=4 Super Yang-Mills from the Plane Wave Matrix Model」

22 T. Kimura (Yukawa Institute for Theoretical Physics, Kyoto University) 1 Nov. RIKEN Seminar「Supergravity on generalized geometry」

23 K. Nagata (Graduate School of Science, Hokkaido University) 14 Nov. RIKEN Seminar「Non-commutative product formulation of Exact Lattice Supersymmetry at Large N」

24 G. Kirilin (Budker Institute of Nuclear Physics) 5 Dec. RIKEN Seminar「Effective theories from diagrams」

25 Y. Kawamura (Department of Physics, Faculty of Science, Shinshu University) 6 Dec. RIKEN Seminar「Beyond Grand Unified Theories on Z_2 Orbifold」

26 M. Sakamoto (Physics Department, Graduate School of Science, Kobe University) 6 Dec. RIKEN Seminar「Supersymmetry in Gauge/Gravity Theories with Extra Dimensions」

27 M. Tanabashi (Department of Physics, Nagoya University) 6 Dec. RIKEN Seminar「General Sum Rules for WW scattering in Higgsless Models」

28 K. Oda (Graduate School of Science/ School of Science, Osaka University) 19 Jan. RIKEN Seminar「A consistent AdS/CFT dual for time-dependent finite tmperature system」

29 A. Hanany (Imperial College London, UK) 19 Jan. RIKEN Seminar「Brane Tilings, M2 Branes, and CS Theories」

30 M. Nitta (Faculty of Business and Commerce, Keio University) 23 Jan. RIKEN Seminar「Non-Abelian Vortices - Five Years Since the Discovery」

31 A. FURUSAKI (RIKEN NishinaCenter) 4 Feb. Colloquium「Topological Insulators」

32 S. Moriyama (Graduate School of Mathematics, Nagoya University) 13 Mar. RIKEN Seminar「Serre Relation and Higher Grade Generators of the AdS/CFT Yangian Symmetry」

Strangeness Nuclear Physics Laboratory

1 T. Myo (Osaka Institute of Technology) 17 Jul. Lab. Seminar「Study of role of tensor correlation in light nuclei based on the tensor-optimized shell model」

2 T. Nagae (Kyoto University) and others 3-6 Aug.「Summer school on exotic nuclei」

3 T. R. Saito, GSI and Mainz University beams at GSI (HypHI) 19 Dec. SNP Seminar「Recent progress on the hypernuclear spectroscopy with heavy ion」

4 H. J. Schulze (INFN, Universita di Catania) 8 Jan. Strangeness Nuclear Physics (SNP) Seminar「Hypernuclei with a Microscopic Lambda-Nucleon Force」

5 E. Hiyama (RIKEN Nishina Center), *el al* 27-28 Feb.「Workshop on the future of physics on quark many-body system」

6 S. Ishikawa (Hosei University) 16-19 Mar. Lab. Seminar「Three-body force effects in three-nucleon scattering process」

Accelerator Applications Research Division

1 K. Takagi (The Wakasa Wan Energy Research Center) 13 Jun. RIKEN Seminar「Biological effects of proton-beam irradiation」

2 H. Takehisa (RIKEN Nishina Center), F-S Che (Nagahama Institute of Bio-Science and Technology) 18 Jul. Radiation Biology Seminar「Mutated gene analysis using array-comparative genomic hybridization」

3   T. Sato（Tohoku Univ.）, Y. Okumoto（Kyoto Univ.）29 Aug. Radiation Biology Seminar「Mutant selection in paddy field is important」

4   Y. Kodaira（Fukushima Pref. Soma High school）Y. Kazama（RIKEN Nishina Center）16 Sep. Radiation Biology Seminar「Educational materials for genetics using Arabidopsis muants」

5   R. Sugiyama（Ajinomoto）T. Abe（RIKEN Nishina Center）24 Oct. Radiation Biology Seminar「Potential use of heavy ion breeding fot functional food factors」

6   A. Ferjani（Department of Education, Tokyo Gakugei University）10 Mar. RIKEN Seminar「FUGU5/AVP1 Activity Is Essential For Early Seedling Development And Organ-Size Control In Arabidopsis」

RIKEN BNL Research Center

1   Howard Georgi（Harvard University）23 Apr. "The Unparticle Scale"

2   Mikhail Shifman（University of Minnesota）19 Nov. "From Vortices in Superconductivity to Quark Confinement"

3   Michele Papucci（IAS, Princeton）25 Feb. "Dark Matter Sees the Light"

JUSTIPEN

1   Anatoli Afanasjev（Department of Physics and Astronomy, Mississippi State University）12 May The next frontier : hyperdeformation

2   Carlos Bertulani（Texas A&M）9 Jun. Pairing strength and odd-even mass differences

3   Betty Tsang（NSCL, Michigan State University）18 Dec. Systematics of neutron spectroscopic factors

CNS

1   P. Roussel-Chomaz（GANIL）2 Apr. Status of the SPIRAL 2 project at GANIL

2   T. Abe（CNS, University of Tokyo）24 Jun. Lattice Calculation of Thermal Properties of Low-Density Neutron Matter with NN Effective Field Theory

3   P. Schuck（Orsay）8 Oct. Alpha-particle condensation in nuclei

4   T. Hashimoto（CNS, University of Tokyo）28 Oct. Direct measurements of the astrophysical nuclearreaction rates with radioactive nuclear beams

5   J. Miyamoto（Weizmann Institute）30 Jan. The Thick Gas Electron Multiplier:its performance and applications

6   J. J. He（IMP, Lanzhou, China）12 Mar. Some Results and Progress in Nuclear Astrophysics Research

AUTHOR INDEX

RIKEN Accelerator Progress Report *vol.* 42