Nuclear Science and Transmutation Research Division
Spin isospin Laboratory

1. Abstract

The Spin Isospin Laboratory pursues research activities putting primary focus on interplay of spin and isospin in exotic nuclei. Understanding nucleosyntheses in the universe, especially those in *r*- and *rp*-processes is another big goal of our laboratory.

Investigations on isospin dependences of nuclear equation of state, spin-isospin responses of exotic nuclei, occurrence of various correlations at low-densities, evolution of spin-orbit coupling are main subjects along the line. We are leading a mass measurement project with the Rare RI Ring project, too. Through the experimental studies, we will be able to elucidate a variety of nuclear phenomena in terms of interplay of spin and isospin, which will in turn, lead us to better understanding of our universe.

2. Major Research Subjects

(1) Direct reaction studies of neutron-matter equation of state
(2) Study of spin-isospin responses with RI-beams
(3) *r*-process nucleosynthesis study with heavy-ion storage ring
(4) Application of spin-polarization technique to RI-beam experiments and other fields
(5) Development of special targets for RI-beam experiments

3. Summary of Research Activity

(1) Direct reaction studies of neutron matter equation of state

Direct reactions induced by light-ions serve as powerful tools to investigate various aspects of nuclei. We are advancing experimental programs to explore equation of state of neutron matter, via light-ion induced reactions with RI-beams.

(1-1) Determination of a neutron skin thickness by proton elastic scattering

A neutron skin thickness is known to have strong relevance to asymmetry terms of nuclear equation of state, especially to a term proportional to density. The ESPRI project aims at determining density distributions in exotic nuclei precisely by proton elastic scattering at 200–300 MeV/nucleon. An experiment for ^{132}Sn that is a flagship in this project has been successfully performed.

(1-2) Asymmetry terms in nuclear incompressibility

Nuclear incompressibility represents stiffness of nuclear matter. Incompressibility of symmetric nuclear matter is determined to be 230 ± 20 MeV, but its isospin dependence still has a large uncertainty at present. A direct approach to the incompressibility of asymmetric nuclear matter is an experimental determination of energies of isoscalar giant monopole resonances (GMR) in heavy nuclei. We have developed, in close collaboration with Center for Nuclear Study (CNS) of University of Tokyo, an active gas target for deuteron inelastic scattering experiments to determine GMR energies. The active gas target has been already tested with oxygen and xenon beams at HIMAC and finally has been applied to a ^{132}Sn experiment at RIBF.

(1-3) Multi-neutron and α-cluster correlations at low densities

Occurrences of multi-neutron and α-cluster correlations are other interesting aspects of nuclear matter and define its low-density behavior. The multi-neutron and α-cluster correlations can be investigated with the large-acceptance SAMURAI spectrometer. The SAMURAI has been already applied to experiments to explore light neutron-rich nuclei close to the dripline. We plan to reinforce experimental capabilities of the SAMURAI by introducing advanced devices such as MINOS (Saclay) and NeuLAND (GSI).

(1-4) Fission barrier heights in neutron-rich heavy nuclei

The symmetry energy has a strong influence on fission barrier heights in neutron-rich nuclei. Knowledge on the fission barrier heights, which is quite poor at present, is quite important for our proper understanding on termination of the *r*-process. We are planning to perform, in collaboration with the TU Munich group, $(p, 2p)$-delayed fission experiments at the SAMURAI to determine the fission barrier heights in neutron-rich nuclei in Pb region.

(2) Study of spin-isospin responses with RI-beams

The study of spin-isospin responses in nuclei forms one of the important cores of nuclear physics. A variety of collective states, for example isovector giant dipole resonances, isobaric analogue states, Gamow-Teller resonances, have been extensively studied by use of electromagnetic and hadronic reactions from stable targets.

The research opportunities can be largely enhanced with light of availabilities of radioactive isotope (RI) beams and of physics of unstable nuclei. There are three possible directions to proceed. The first direction is studies of spin-isospin responses of unstable nuclei via inverse-kinematics charge exchange reactions. A neutron-detector array WINDS has been constructed, under a collaboration of CNS, Tokyo and RIKEN, for inverse kinematics (p, n) experiments at the RI Beam Factory. We have already applied WINDS to the (p, n) experiments for ^{12}Be, ^{132}Sn and plan to extend this kind of study to other exotic nuclei.

The second direction is studies with RI-beam induced charge exchange reaction. RI-beam induced reactions have unique properties which are missing in stable-beam induced reactions and can be used to reach the yet-to-be-discovered states. We have constructed the SHARAQ spectrometer and the high-resolution beam-line at the RI Beam Factory to pursue the capabilities of RI-beam induced reactions as new probes to nuclei. One of the highlights is an observation of β^+ type isovector spin monopole resonances (IVSMR) in ^{208}Pb and ^{90}Zr via the $(t, ^3\mathrm{He})$ reaction at 300 MeV/nucleon.

The third direction is studies of neutron- and proton-rich nuclei via stable-beam induced charge exchange reactions, which is conducted under collaboration with Research Center for Nuclear Physics (RCNP), Osaka University. We have performed the double

charge exchange ^{12}C(^{18}O, ^{18}Ne)^{12}Be reaction at 80 MeV/nucleon to investigate structure of a neutron-rich ^{12}Be nucleus. Peaks corre- sponding to ground and excited levels in ^{12}Be have been clearly observed. Another double charge exchange reaction, (^{12}C, ^{12}Be(0^+)) are being used to search for double Gamow-Teller resonances.

(3) *r*-process nucleosynthesis study with heavy-ion storage ring

Most of the *r*-process nuclei become within reach of experimental studies for the first time at RI Beam Factory at RIKEN. The Rare RI Ring at RIBF is the unique facility with which we can perform mass measurements of *r*-process nuclei. Construction of the Rare RI Ring started in FY2012 in collaboration with Tsukuba and Saitama Universities. A major part of the ring has been completed and the commissioning run is planned in FY2014.

We are planning to start precise mass measurements of *r*-process nuclei soon. A series of experiments will start with nuclei in the $A = 80$ region and will be extended to heavier region.

(4) Application of spin-polarization technique to RI-beam experiments and other fields

A technique to produce nuclear polarization by means of electron polarization in photo-excited triplet states of aromatic molecules can open new applications. The technique is called "Tripletd-DNP." A distinguished feature of Triplet-DNP is that it works under a low magnetic field of 0.1–0.7 T and temperature higher than 100 K, which exhibits a striking contrast to standard dynamic nuclear polarization (DNP) techniques working in extreme conditions of several Tesla and sub-Kelvin.

We have constructed a polarized proton target system for use in RI-beam experiments. Recent experimental and theoretical studies have revealed that spin degrees of freedom play a vital role in exotic nuclei. Tensor force effects on the evolution of shell and possible occurrence of *p*-*n* pairing in the proton-rich region are good examples of manifestations of spin degrees of freedom. Experiments with the target system allow us to explore the spin effects in exotic nuclei. It should be noted that we have recently achieved a proton polarization of 40% at room temperature in a pentacene-d_{14} doped *p*-terphenyl crystal.

Another interesting application of Triplet-DNP is sensitivity enhancement in NMR spectroscopy of biomolecules. We started a new project to apply the Triplet-DNP technique to study protein-protein interaction via two-dimensional NMR spectroscopy, in close collaboration with biologists and chemists.

(5) Development of special targets for RI-beam experiments

For the research activities shown above, we are developing and hosting special targets for RI-beam experiments listed below:

(a) Polarized proton target (described in (4))
(b) Thin solid hydrogen target
(c) MINOS (developed at Saclay and hosted by the Spin Isospin Laboratory)

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List of Publications & Presentations

Publications

[Original Papers]

V. P. Ladygin, A. V. Averyanov, E. V. Chernykh, D. Enache, Yu. V. Gurchin, A. Yu. Isupov, M. Janek, J. -T. Karachuk, A. N. hrenov, D. O. Krivenkov, P. K. Kurilkin, N. B. Ladygina, A. N. Livanov, O. Mezhenska, S. M. Piyadin, S. G. Reznikov, Y. T. Skhomenko, A. A. Terekhin, A. V. Tishevsky, T. Uesaka, and I. S. Volkov, "Deuteron analyzing powers A_y, A_{yy}, and A_{xx} in dp-elastic scattering at large transverse momenta," JPS Conf. Proc. **37**, 020902 (2022).

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Presentations

[International Conferences/Workshops]

H. Sagawa (invited), "What can we learn from the nuclear ground state densities?," 6th Topical Workshop on Modern Aspects in Nuclear Stracutre, Bormio, Italy, February 6–11, 2022.

H. Sagawa (invited), "Beyond mean field model for nuclear collective states," The 16th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG2022), Hanoi, Vietnam, October 25–28, 2022.

H. Sagawa (invited), "What can we learn from the nuclear ground state densities?," Physics of RI: Recent progress andperspectives, RIKEN, Saitama, Japan, May 30–June 1, 2022.

H. Sagawa (oral), "Some topics of isoscalar spin-triplet pairing," YIPQS long-term workshop, "Mean-field and cluster dynamics in nuclear systems 2022 (MCD2022), Kyoto University, Kyoto, May 9–June 17, 2023.

H. Sagawa (invited), "What can we learn from the nuclear ground state densities?," Focus Program: A quest for exotica in rare-earth elements, Pohang, Korea, August 22–26, 2022.

J. Tanaka (invited), "Clustering phenomena in dilute neutron-rich matter," The 15th Asia Pacific Physics Conference (APPC15) August 21–26, 2022.

Y. Kubota (invited), "Surface localization of the dineutron in nuclei," in Halo Week 2022, Bergen, Norway, 2022.

Y. Kubota (oral), "Recent updates on SAMURAI18 experiment," in SAMURAI International Collaboration Workshop 2022, Ookayama, Japan, 2022.

Y. Kubota (oral), "SAMURAI: Recent advances in analysis and prospects for future experiments," in RIBF Users Meeting 2022.

Y. Hijikata (oral), "Developmetn of gaseous Xe scintillator for particle identification of high-intensity RI beams," The 2022 Annual Meeting of the JSPS/NSFC/NRF A3 Foresight Program, Osaka, Japan, February 14, 2023.

T. Tsuji (oral), "Development of TOGAXSI array," SAMURAI International Collaboration Workshop 2022, Meguro-ku, Tokyo (Tokyo titech University), September 2–3, 2022.

T. Tsuji (oral), "Development of large GAGG:Ce calorimeter for measurements of the cluster knockout reactions," A3 Foresight Annual Meeting 2022, Osaka, Japan (OsakaInternational Convention Center), February 13–15, 2023.

T. Uesaka (invited), "Clustering in heavy nuclei probed with knockout reactions," 6th Topical Workshop on Modern Aspects in Nuclear Stracutre, Bormio, Italy, February 6–11, 2022.

T. Uesaka (invited), "Recent progress in nuclear cluster physics," 28th International Nuclear Physics Conference (INPC 2022), Cape town, South Africa, September 11–16, 2022.

T. Uesaka (invited), "ONOKORO project—knockout reaction studies of clusters in heavy nuclei—," Direct Reactions with Exotic Beams (DREB2022), Santiago de Compostela, Spain, June 26–July 1, 2022.

J. Tanaka (poster), "Detector array TOGAXSI for inverse-kinematics cluster and nucleon knockout reaction experiment," EMIS 2022, Daejeon, Korea, October 3–7, 2022.

Y. Hijikata (poster), "Development of gaseous Xe scintillator for particle identification of high-intensity and heavy-ion beams," EMIS 2022, Daejeon, Korea, October 3–7, 2022.

R. Tsuji (poster) , "Development of large GAGG:Ce calorimeter for measurements of the cluster knockout reactions," EMIS2022, Dejean, Korea, October 3–7, 2022.

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[Domestic Conferences/Workshops]

田中純貴（招待講演), 「原子核基底状態のアルファクラスターと ONOKORO プロジェクト」, 日本物理学会 2023 年春季大会, シンポジウム講演, 2023 年 3 月 22–25 日.

久保田悠樹（招待講演), 「ノックアウト反応で調べるボロミアン核のダイニュートロン相関」, RCNP 研究会「微視的系と巨視的系における核子対凝縮相」, 茨木市 (大阪大学核物理研究センター), 2022 年 9 月 26–28 日.

立石健一郎（口頭論文), 「トリプレット DNP による室温核偏極: 原理・装置・現状の課題」, DNP 研究会, 豊中市 (大阪大学南部陽一郎ホール), 2022 年 7 月 12 日.

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立石健一郎（口頭論文), 「Development of High-temperature Nuclear Polarization Method for Hypersensitive NMR Spectroscopy」, Frontier of Dynamic Structural Biology, 吹田市 (大阪大学), 2022 年 10 月 17–18 日.

土方佑斗（口頭論文), 「錫 112 の弾性散乱と錫同位体でのアイソスカラー・アイソベクトル密度分布変化」, おのころ戸隠夏合宿, 長野市 (JA 長野県ビル), 2022 年 7 月 29–31 日.

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辻崚太郎（口頭論文), 「$^{40-52}$Ca(p, pX) とクラスター種の同位体依存性」, おのころプロジェクト戸隠夏合宿, 長野市 (JA 長野県ビル), 2022 年 07 月 29–30 日.

土方佑斗（ポスター), 「原子核実験の先端データ収集システム—標準化と将来—」, 茨木市 (大阪大学 RCNP), 2023 年 3 月 16 日.

Awards

久保田悠樹, 第 29 回 原子核談話会新人賞.

久保田悠樹, 第 17 回 日本物理学会若手奨励賞.

Other

土方佑斗（パネルディスカッション), 「原子核実験の先端データ収集システム—標準化と将来—」, 茨木市（大阪大学 RCNP), 2023 年 3 月 16 日.