Research Facility Development Division
Instrumentation Development Group
SLOWRI Team

1. Abstract

The SLOWRI team develops, operates and improves SLOW RI beam production devices and related systems, and uses these devices and systems to conduct experimental programs at RIBF. As the heart of SLOWRI, we have developed RF carpet type cryogenic He gas catchers (RFGC). Two RFGCs are currently in operation to deliver slow RI beams converted from fast RIs produced with fragmentation or inflight fission on RIPS and BigRIPS. These RFGCs are directly combined with muti-reflection time-of-flight mass spectrographs (MRTOF-MS) for precise mass measurements tailored to user's experimental programs. Especially, the RFGC combined with a MRTOF-MS installed behind ZeroDegree spectrometer of BigRIPS is being operated symbiotically reusing RIs from other experiment conducted upstream without extra costs. To date, masses on more than 80 RIs provided with BigRIPS have been successfully measured. A lot of user's experimental programs for precise mass measurements will be conducted in SLOWRI project soon. An Ar gas catcher at F2 of BigRIPS was also installed to rescue RI that would otherwise be discarded without being used for experiments. The RI is caught with the Ar gas catcher, laser resonant ionized and delivered as a slow RI beam in parasitic operating mode (PALIS). The off- and online-commissioning of PALIS is underway.

2. Major Research Subjects

(1) Development, operation and upgrade of SLOW RI beam production devices and related systems
(2) Development and operation of multi-reflection time-of-flight mass spectrographs and to conduct precision mass measurements of short-lived nuclei
(3) Development of a parasitic slow RI beam production method using resonance laser ionization

3. Summary of Research Activity

(1) Development of RF carpet type cryogenic He gas catchers (RFGCs)

The fast (>100 MeV/nucleon) RI beams can be stopped in helium gas and extracted as slow (<100 eV) RI beams from a RF carpet type cryogenic He gas cell (RFGC). At RIBF, two RFGCs are in operation at the SLOWRI project: one is a 30-cm-long RFGC consisting of DC ring electrodes and a RF carpet. It is located behind GARIS-II at E6 of RIBF and is used in combination with a MRTOF-MS for precise mass measurements of superheavy nuclides. Also, a 9 MBq ^{252}Cf fission source has recently been installed just in front of the He gas catcher. Even off-line, mass measurements on fission fragments have continued and several first mass measurements were performed.

Second one is a 50-cm-long RFGC installed behind ZeroDgree spectrometer of BigRIPS. This RFGC contains a three stage RF-carpet structure: a gutter RF carpet (1st carpet) for the collection thermal ions in the cell into a small slit, a narrow (about 10 mm) traveling-wave RF-carpet (2nd carpet) for collection of ions from the gutter carpet and for transporting the ions towards the exit, and a small RF carpet for extraction from the gas cell. The off-line test has been completed in FY2019. The on-line commissioning has been successfully performed symbiotically using RIs provided with BigRIPS during HiCARI campaign in FY2020. During the on-line commissioning, precise mass measurements were also performed. In FY2021, the first experiment approved in NP-PAC of RNC has been performed, which has aimed the mass measurement in the vicinity of the double magic nucleus of ^{78}Ni. As the result, masses of ^{74}Ni and ^{75}Ni have been measured with high precision less than 20 keV. In FY 2022, a ^{248}Cm source has been installed just behind the mylar window of the gas cell. The measured extraction efficiencies on the fission products emitted from the source after stopping in the He gas have been currently reached several to about 30% of the sum of singly-, doubly- and triply-charged ions, depending on elements. Several improvements in order to improve the efficiencies are underway using the fission fragments from the source. Mass measurements on experimental programs already approved in NP-PAC of RIBF will be performed soon. A final version of the RFGC, 1 m long and with increased helium gas pressure, is also in preparation and will be installed in SD4 at BigRIPS.

(2) Conduct of precise mass measurements using MRTOF-MSs combined with RFGCs

The MRTOF, called as SHE-MASS, is combined with the RFGC behind GARIS-II of E6. Mass measurements of superheavy elements of Db isotopes have been conducted. As a result, the mass on ^{257}Db superheavy nucleus was determined for the first time. The mass measurements on superheavy nuclide, proton rich nuclide and fission products emitted from intense Cf source have been performed.

The MRTOF-MS, called as ZD-MRTOF, is located behind ZDS of BigRIPS in combination with the 50 cm-long RFGC. Currently, the mass resolving power has been reached at 1 million. Since the location of the ZD-MRTOF is just in front of the beam dump of ZDS, mass measurements have been conducted symbiotically re-using RIs from other experiment conducted upstream without extra costs. To date, the masses on more than 80 RIs provided from BigRIPS have been measured. Among them, three isotope masses have been measured for the first time and mass uncertainties of eleven isotope have been significantly improved from the previous ones. For example, the mass uncertainties have been reduced down to the order of 10 keV for ^{56,58}Ti and $^{56\text{-}59}$V and nonexistence of the N = 34 empirical two neutron shell-gaps on Ti and V isotopes are revealed experimentally with the new precision achieved.

We have a plan to increase this versatile and portable instrumentation at RIBF: an MRTOF-MS is being installed behind GARIS-III, and a plan is underway to install an MRTOF-MS with the RFGC behind SD4 at BigRIPS, which will lead to more opportunities to study unexplored nuclear species.

(3) Development of a parasitic slow RI beam production method using resonance laser ionization (PALIS)

More than 99% of RIs produced in projectile fission or fragmentation at BigRIPS of RIBF are simply dumped into the first dipole magnet and the slits. The SLOWRI project proposed a new method called PALIS, which uses a compact Ar gas catcher and resonant laser ionization to rescue such precious RI. The thermalized RIs in a cell filled with Ar gas can be quickly neutralized and transported to the exit of the cell by gas flow. Irradiation of resonance lasers at the exit ionizes neutral RI atoms selectively. PALIS is located at F2 of BigRIPS and is undergoing off- and on-line commissioning.

At F2, due to high radiation from a beam dump, it was found to be not easy to handle ions using electric ion guides. Therefore, a 70-cm-long gas pipe from the Ar gas cell was newly installed to transport RIs to relatively low radiation area thanks for the Ar gas flow. In FY2021, we have confirmed the transport of ions of interest downstream of the ion guide behind the gas pipe using α-emitting Ac isotopes provided with BigRIPS. Also, we have found a lot of contaminant ions from the gas cell, which are originated from impurities in the gas. To reduce the influence of such contaminant, a quadrupole mass filter has been installed downstream of the ion guide. In FY2023, an on-line test for resonant laser ionization is planned.

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List of Publications & Presentations

Publications

[Original Papers]

S. Iimura, M. Rosenbusch, A. Takamine, Y. Tsunoda, M. Wada, S. Chen, D. S. Hou, W. Xian, H. Ishiyama, S. Yan, P. Schury, H. Crawford, P. Doornenbal, Y. Hirayama, Y. Ito, S. Kimura, T. Koiwai, T. M. Kojima, H. Koura, J. Lee, J. Liu, S. Michimasa, H. Miyatake, J. Y. Moon, S. Nishimura, S. Naimi, T. Niwase, A. Odahara, T. Otsuka, S. Paschalis, M. Petri, N. Shimizu, T. Sonoda, D. Suzuki, Y. X. Watanabe, K. Wimmer, and H. Wollnik, "A new study of the $N = 32$ and $N = 34$ shell gap for Ti and V by the first high-precision MRTOF mass measurements at BigRIPS-SLOWRI," Phys. Rev. Lett. **130**, 012501 (2023).

M. Rosenbusch, M. Wada, S. Chen, A. Takamine, S. Iimura, D. Hou, W. Xian, S. Yan, P. Schury, Y. Hirayama, Y. Ito, H. Ishiyama, S. Kimura, T. Kojima, J. Lee, J. Liu, S. Michimasa, H. Miyatake, M. Mukai, J. Y. Moon, S. Nishimura, S. Naiumi, T. Niwase, T. Sonoda, Y. X. Watanabe, and H. Wolnik, "The new MRTOF mass spectrograph following the ZeroDegree spectrometer at RIKEN's RIBF facility," Nucl. Instrum. Methods Phys. Res. B **1047**, 167824 (2023).

Y. Hirayama, M. Mukai, Y. X. Watanabe, P. Schury, H. Nakada, J. Y. Moon, T. Hashimoto, S. Iimura, S. C. Jeong, M. Rosenbusch, M. Oyaizu, T. Niwase, M. Tajima, A. Taniguchi, M. Wada, and H. Miyatake, "In-gas-cell laser resonance ionization spectroscopy of ^{200,201}Pt," Phys. Rev. C **106**, 034326 (2022).

Presentations

[International Conferences/Workshops]

S. Iimura (invited), "A new study of $N = 34$ subshell structure probed by high-precision mass measurements," JSPS/NSFC/NRF A3 Foresight Program, "Nuclear Physics in the 21st Century," Osaka, Japan, February 13–15, 2023.

A. Takamine, M. Rosenbusch, M. Wada, S. Iimura, D. Hou, W. Xian, S. Chen, J. M. Yap, H. Ishiyama, P. Schury, S. Nishimura, T. Niwase, S. Kimura, Y. Hirayama, Y. Ito, T. M. Kojima, J. Lee, J. Liu, S. Michimasa, H. Miyatake, J. Y. Moon, M. Mukai, S. Naimi, T. Sonoda, H. Ueno, P. Vi, Y. X. Watanabe, S. Yan, T. T. Yeung, and H. Wollnik, "Development of the new helium gas catcher and nuclear mass measurements with the new MRTOF-MS system behind the ZeroDegree spectrometer at RIKEN BigRIPS," The 19th International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS 2022), Daejong, Korea, October 3–7, 2022.

M. Rosenbusch, M. Wada, S. Chen, A. Takamine, S. Iimura, D. Hou, W. Xian, S. Yan, P. Schury, Y. Hirayama, Y. Ito, H. Ishiyama, S. Kimura, J. Lee, J. Liu, S. Michimasa, H. Miyatake, J. Y. Moon, S. Nishimura, S. Naimi, T. Niwase, Y. X. Watanabe, P. Vi, H. Wollnik, and J. M. Yap, "High-precision MRTOF mass measurements of radioactive isotopes at RIKEN's RIBF facility: Recent projects for mirror potentials, wideband mass accuracy, and ion selection," The 19th International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS 2022), Daejong, Korea, October 3–7, 2022.

M. Rosenbusch, "Exploring exotic nuclei by high-precision MRTOF mass measurements: The new ion catcher and mass spectrograph at RIKEN's RIBF facility," The 8th International Conference on Trapped Charged Particles and Fundamental Physics (TCP 2022), Glashütten, Germany, September 25–30, 2022.

H. Ishiyama, "Toward mass measurement of neutron-rich nuclei in the vicinity of $N = 126$," Workshop for Uniqueness of the ^{208}Pb beam at RIBF, Online, September 27, 2022.

M. Rosenbusch (invited), "New nuclear masses, recent and present developments, and future opportunities of the MRTOF-MS at the ZeroDegree spectrometer," RIBF Users Meeting 2022, Online, September 20–22, 2022.

S. Iimura (invited), "A new study of the $N = 32$ and $N = 34$ shell gap for Ti and V by the first high-precision MRTOF mass measurements at BigRIPS-SLOWRI," RIBF Users Meeting 2022, Online, September 20–22, 2022.

A. Takamine (invited), "Nuclear mass measurements with the new MRTOF-MS system at the ZeroDegree spectrometer of BigRIPS," 28th International Nuclear Physics Conference (INPC 2022), Cape Town, South Africa, September 11–16, 2022.

H. Ishiyama (invited), "Present status of SLOWRI," SSRI-PNS collaboration meeting 2022, Online, September 1–2, 2022.

[Domestic Conferences/Workshops]

M. Rosenbusch, S. Iimura, A. Takamine, Y. Tsunoda, M. Wada, S. Chen, D. S. Hou, W. Xian, H. Ishiyama, S. Yan, P. Schury, H. Crawford, P. Doornenbal, Y. Hirayama, Y. Ito1, S. Kimura, T. Koiwai, T. M. Kojima, H. Koura, J. Lee, J. Liu, S. Michimasa, H. Miyatake, J. Y. Moon, S. Naimi, S. Nishimura, T. Niwase, A. Odahara, T. Otsuka, S. Paschalis, M. Petri, N. Shimizu, T. Sonoda, D. Suzuki, Y. X. Watanabe, K. Wimmer, and H. Wollnik, "The SLOWRI/MRTOF-MS project at BigRIPS/ZeroDegree," 日本物理学会 2022 年度春季年会, オンライン, 2023 年 3 月 23–25 日.

飯村俊, M. Rosenbusch, 高峰愛子, 和田道治, S. Chen, D. Hou, J. Liu, W. Xian, S. Yan, P. Schury, 木村創大, 庭瀬暁隆, 伊藤由太, 園田哲, 小島隆夫, 渡辺裕, 平山賀一, 宮武宇也, S. Naimi, 道正新一郎, 西村俊二, 小田原厚子, 石山博恒, 角田佑介, 清水則孝, 大塚孝治, 「BigRIPS SLOWRI における ZD-MRTOF 装置を用いた中性子過剰 Sc, Ti, V 核の系統的核構造研究」, 日本物理学会 2022 年度秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

庭瀬暁隆, 渡辺裕, 平山賀一, 向井もも, P. Schury, A. N. Andreyev, 飯村俊, 石山博恒, 鄭淳讃, 宮武宇也, M. Rosenbusch, 谷口秋洋, 和田道治, 「精密質量測定による新同位体 ^{241}U の発見」, 日本物理学会 2022 年度秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

[Seminar]

M. Rosenbusch (invited), "A first review of the SLOWRI-MRTOF mass spectrograph following the ZeroDegree spectrometer at BigRIPS," RIBF seminar, Wako, Japan, February 14, 2023.

Press Release

マルコローゼンブッシュ, 飯村俊, 他, 「チタン・バナジウム中性子過剰同位体で新魔法数の消失を観測—精密質量測定による原子核構造のより深い理解に期待—」, KEK, RIKEN, 大阪大学, 2023 年 1 月 6 日.