Nuclear Science Research Division
Nuclear Structure Research 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 200 RIs provided with BigRIPS have been successfully measured. A lot of user's experimental programs for precise mass measurements have been conducted in SLOWRI project. 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. A final version of the RFGC with dual cryocoolers to suppress contaminated molecules 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 Sc, Ti and V isotopes, the mass uncertainty of ^{55}Sc has been improved with a factor of two and ones of ^{56,58}Ti and $^{56\text{-}59}$V have been improved with one order of magnitude down to the order of 10 keV. As the result, the nonexistence of the $N = 34$ shell gaps has been experimentally revealed with the new precision achieved. For Ge, Se and As isotopes, the mass uncertainties of ^{86}Ge and ^{90,91}Se have been significantly reduced below 10 keV and the masses of ^{88,89}As have been measured for the first time. The two neutron separation energies on Se isotopes have been determined beyond $N = 56$. Also, the impact of the obtained masses on *r*-process nucleosynthesis in lighter mass region is discussed, demonstrating the importance of precise mass measurements. The mass of ^{112}Mo has been measured for the first time with the mass uncertainty of less than 10 keV. The newly obtained two-neutron separation energies for Mo isotopes up to $N = 70$ show a smooth trend. In FY2024, masses on about 120 RIs were measured. Although the data analysis is on-going, 21 isotope masses can be obtained for the first time. For 14 isotopes, significant improvement in mass precision by a factor of 2 or more, or a large deviation (>50 keV) in mass values, can be also obtained compared to that of AME2020. Several physical outputs are expected to be obtained in the measured regions, including proton-rich Sn isotopes down to a double magic nucleus of ^{100}Sn, ^{136,137}Sn isotopes located on a route escaping from the 2nd *r*-process peak, and proton-rich isotopes from Y to Cd with $N = Z$.

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 FY2024, installation of a new MRTOF was completed.

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List of Publications & Presentations

Publications

[Original Papers]

J. Y. Moon, P. H. Schury, M. Wada, Y. Hirayama, H. Miyatake, Y. X. Watanabe, H. Ishiyama, M. Rosenbusch, Y. Ito, A. Takamine, T. Niwase, H. Wollnik, Z. korkulu, T. Shin, and J. Lee, "Construction of a new multi-refection time-of-fight mass spectrograph at RAON," Journal of the Korean Physical Society `https://doi.org/10.1007/s40042-024-01237-x`.

T. Hashimoto, H. J. Yim, J. H. Kim, Y. -H. Park, S. Heo, K. H. Yoo, C. C. Yun, H. Ishiyama, and J. H. Lee, "Design and commissioning of the ISOL beamline at the RAON facility," Nucl. Instrum. Methods Phys. Res. B **556**, 165504 (2024).

S. Kimura, M. Wada, H. Haba, H. Ishiyama, S. Ishizawa, Y. Ito, T. Niwase, M. Rosenbusch, P. Schury, and A. Takamine, "Comprehensive mass measurement study of ^{252}Cf fission fragments with MRTOF-MS and detailed study of masses of neutron-rich Ce isotopes," Phys. Rev. C **110**, 045810 (2024).

Y. Hirayama, M. Mukai, P. Schury, Y. X. Watanabe, S. Iimura, H. Ishiyama, S. C. Jeong, H. Miyatake, T. Niwase, M. Rosenbusch, A. Takamine, A. Taniguchi, and M. Wada, "Helium gas cell with RF wire carpets for KEK Isotope Separation System," Nucl. Instrum. Methods Phys. Res. A **1058**, 168838 (2024).

Presentations

[International Conferences/Workshops]

S. Iimura, “Investigating Shell Structure at N = 32 and 34 in Neutron-Rich Nuclei Using High-Precision Mass Measurements,” PCM2025 International Symposium〜Single-particle and Collective Motions from Nuclear Many-body Correlation〜, Aizu University, March 4–7, 2025.

W. Xian (invited), “Recent status of ZD-MRTOF and precision mass of neutron-rich A 90 nuclei constrain element abundances,” RIBF Users Meeting 2025, RIKEN, January 21, 2025.

M. Rosenbusch (invited), “The MRTOF mass measurement project at BigRIPS,” MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions, RIKEN, July 4–5, 2024.

J. M. Yap (invited), “Operation and perspectives of the ZeroDegree helium gas catcher at RIKEN,” MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions, RIKEN, July 4–5, 2024.

H. Ishiyama (invied), “Present status of SLOWRI,” SSRI-PNS Collaboration Meeting 2024, RIKEN, September 4–5, 2024.

[Domestic Conferences/Workshops]

石山博恒 (招待講演), Hoi Hin Siu, 松村理久, 武重祥子, Chaoyi Fu, Phong Vi, Marco Rosenbush, 飯村俊, 池田時浩, 小島隆夫, 磯部忠昭, 佐藤広海, 鈴木大介, 馬場秀忠, 田中鐘信, 西村俊二, 本林透, Jenny Lee, Seonhoo Choi, 上野秀樹, 櫻井博義,「理研ペレトロン加速器を用いた仁科スクール 2023」, 第 36 回タンデム研究会, 理研, 2024 年 7 月 27–28 日.