Research Facility Development Division
Instrumentation Development Group

1. Abstract

This group develops the core-experimental instruments at the RI Beam Factory. Three projects are currently going on. SCRIT is the world's first experimental facility for electron scattering of unstable nuclei and was constructed off the main beamline of RIBF. After the success of the world's first electron scattering experiment with online-produced unstable nuclei, we conducted several experiments for studying the properties of trapped ions inside SCRIT. In addition, for the upgrade of electron beam power, a new power supply of klystron was installed and commissioned. The Rare-RI Ring is an event-by-event-operated heavy ion storage ring for precise mass measurement of extremely rare exotic nuclei. It is currently accepting applications for experimental proposals and has already conducted PAC-approved experiments. In 2024, we conducted the machine-study experiment to test the updated kicker system, the newly installed steering magnets and the rectangular-type Schottky pick-up with the primary beam, ^{124}Xe. The successful operation of these devices have enabled stable measurements, dramatically increased extraction yields, and the clean frequency spectra measurement with short measurement time. For further development of mass measurement, the Schottky cavity doublet was installed in a straight section of R3. The compact heavy-ion storage ring RUNBA is an R&D machine for the development of beam recycling techniques for nuclear reaction research on rare isotopes. This is currently under construction and some of the critical components of RUNBA are currently undergoing technical development.

All instrumentation are designed to maximize the research potential of the world's most intense RI beams, and dedicated RI Beam Factory equipment makes the experimental challenge possible. The experimental technique and experience accumulated in this group provide opportunities for new experimental challenges and form the basis for the future development of the RIBF.

2. Major Research Subjects

(1) SCRIT Project (electron scattering off unstable nuclei)
(2) Rare-RI Ring Project (precise mass measurement)
(3) RUNBA project (Beam recycling techniques)

3. Summary of Research Activity

We are developing beam manipulation techniques to carry out the above projects. These are high-quality slow RI beam production technology (SCRIT), ion beam trapping technology (SCRIT), and beam accumulation technology in a storage ring (Rare RI Ring, RUNBA). The technical know-how accumulated in the project will play a major role in the next generation of RIBF.

SCRIT is a novel technique to form internal target in an electron storage ring. Positive ions are three dimensionally confined in the electron beam axis by transverse focusing force given by the circulating electron beam and applied electrostatic longitudinal mirror potential. The created ion cloud composed of RI ions injected from outside works as a target for electron scattering. Construction of the SCRIT electron scattering facility has been started in 2009. Electron beam accelerated up to 150 MeV by the electron accelerator RTM is injected to the storage ring SR2. Typical accumulation current in SR2 is 250–300 mA at the energy range of 120–300 MeV that is required energy range in electron scattering experiment. The SCRIT device was inserted in the straight section of SR2 and connected to an ISOL named ERIS (Electron-beam-driven RI separator for SCRIT) by 20-m long low energy ion transport line. A buncher system based on RFQ linear trap named FRAC (Fringing-RF-field-Activated dc-to-pulse converter) was inserted in the transport line to convert the continuous beam from ERIS to pulsed beam, which is acceptable for SCRIT. The detector system WiSES consisting of a high-resolution magnetic spectrometer, drift chambers and trigger scintillators, was constructed, and it has a solid angle of 100 msr, energy resolution of 10^{-3}, and the scattering angle coverage of 25–55 degrees. A wide range of momentum transfer, 80–300 MeV/c, is covered by changing the electron beam energy from 150 to 300 MeV. In 2024, we conducted the test experiments on the ion trapping characteristics of the SCRIT method and we also tested the improved luminosity monitor system. Using ions of stable nuclei, the ion trapping with the SCRIT method was characterized by measuring the charge-state distribution depend on trapping time and obtaining the results of total charge measurements, including changes in the number of trapped ions and their contribution to electron scattering. This provided data suggesting that differences in the spatial and momentum distributions of ions in the SCRIT trap with different charge states are important for efficient electron scattering experiments. Information on kinetic energy in the SCRIT device was also evaluated by investigating the trajectory of the extracted ions with help of simulation. Further detailed investigations to deduce more information of the ion trapping are planned in near future. Concerning the luminosity monitor system, the position detector was improved to achieve higher position resolution. This new detector is expected to provide a clearer distribution of bremsstrahlung photons emitted by target ions in the SCRIT device and improve the accuracy of the estimation of absolute luminosity. The upgrade project of the SCRIT facility for the ^{132}Sn experiment has already started. The main subject is to increase the intensity of unstable nuclei by more than two orders of magnitude. To achieve this, the electron beam power is being increased from the current 10 W to 1 kW. As a first step, in 2024, a new modulator power supply and klystron were installed. Furthermore, to improve the stability of the electron storage ring, a Landau cavity was installed in the straight section opposite the SCRIT system. The commissioning and tuning of these new devices are an ongoing process.

The Rare RI Ring is an event-by-event based mass measurement system, designed specifically for extremely low-producing isotopes. We carried out PAC-approved experiments and successfully measured the masses of ^{74,76}Ni, ^{122}Rh, ^{123,124}Pd and ^{125}Ag for the first time. To improve mass resolution and efficiency, the first-response kicker system and optical tuning system are being improved. In the commissioning experiments up to 2017, we confirmed the unique performances of R3 and demonstrated the time-of-

flight isochronous mass measurement method. We have realized in forming the precise isochronous field of less than 5 ppm with wide momentum range of $\Delta p/p = \pm 0.5\%$. Another performance required for R3 is to efficiently seize hold of an opportunity of the mass measurement for rare-RIs produced unpredictably. It was realized by constructing the Isotope-Selectable Self-trigger Injection (ISSI) scheme which pre-identified rare-RI itself triggers the injection kicker magnets. Key device was a fast response kicker system that has been successfully developed. Full activation of the kicker magnetic field can be completed within the flight time of the rare-RI from an originating point (F3 focal point in BigRIPS) of the trigger signal to the kicker position in R3. Since R3 circulates, in principle, only one event, we fabricated high-sensitive beam diagnostic devices in the ring. One of them is a cavity type of Schottky pick-up installed in a straight section of R3. We conducted several mass measurements for neutron rich nucleus far from stability. Apart from ^{123}Pd, for which the results have already been published, the final mass values of other measured nuclei, such as Ni-isotopes, will be published soon. In 2023, the kicker system was improved by replacing the capacitors of the pulsed power supplies of the kicker magnets. Two steering magnets were also installed at the appropriate locations in the injection beam line to R3 to adjust the vertical beam direction. In 2024, the commissioning experiment with these devices was conducted using the primary beam, ^{124}Xe. During the commissioning experiment, stable operation of the pulsed power supplies of the kicker magnets were obtained. Furthermore, the extraction yield was successfully increased by adjusting the vertical beam position at the kicker center using two vertical steering magnets. These results not only mean that mass measurement experiments can be resumed, but also that measurement efficiency can be improved. In addition, a new type of resonant Schottky pick-up, which is a rectangular-type cavity, was developed for extension of the frequency-band adjustment range, miniaturization, cost reduction, and sensitivity improvement. We also tested this new cavity with ^{124}Xe beam. As a result, the new cavity enabled clean frequency spectra to be obtained even with short measurement times, 10 ms. The timing of the injection and extraction of a single particle was clearly obtained, and frequency differences due to differences in momentum were also measured. For further development of mass measurement, the Schottky cavity doublet (SCD) was installed in a straight section of R3. The SCD consists of a position-sensitive resonant Schottky pick-up with an elliptical shape and a cylindrical shape resonant Schottky pick-up. The beam position, and hence the momentum, can be derived from the difference in signal intensity of the two cavities. Therefore, the momentum correction of the measured particle in the mass measurement can be applied without any changing the beam conditions (charge state, energy, angle). A commissioning experiment of the SCD will be performed soon.

Beam recycling technology allows the circulation of RI beams to be maintained in a storage ring with a thin internal target until a nuclear reaction occurs. To establish beam recirculation, the increase in energy width and emittance needs to be compensated for using a fast feedback system. We have demonstrated the possibility of compensation in an analytical way and found the properties of EDC and ADC devices necessary for compensation. To develop these new technologies, a compact heavy ion storage ring (RUNBA) connected to ISOL (ERIS) is under construction at the SCRIT facility. Under a research cooperation agreement with ICR in Kyoto University, technical development of the main components required for RUNBA *i.e.* the charge breeder, energy dispersion corrector, angular diffusion corrector and internal target system are underway. In 2024, we continued the development of the simulation code based on the analytical model to investigate the dynamics for RUNBA. In addition, we started the development of the test equipment for testing the basic technology of generic RI targets using the SCRIT method.

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List of Publications & Presentations

Publications

[Original Papers]

D. Nagae, S. Omika, Y. Abe, Y. Yamaguchi, F. Suzaki, K. Wakayama, N. Tadano, R. Igosawa, K. Inomata, H. Arakawa, K. Nishimuro, T. Fujii, T. Mitsui, T. Yamaguchi, T. Suzuki, S. Suzuki, T. Moriguchi, M. Amano, D. Kamioka, A. Ozawa, S. Naimi, Z. Ge, Y. Yanagisawa, H. Baba, S. Michimasa, S. Ota, G. Lorusso, Yu. A. Litvinov, M. Wakasugi, T. Uesaka, and Y. Yano, "Isochronous mass spectrometry at the RIKEN Rare-RI Ring facility," Phys. Rev. C **110**, 014310 (2024).

D. Freire-Fernandez, W. Korten, R. J. Chen, S. Litvinov, Yu. A. Litvinov, M. S. Sanjari, H. Weick, F. C. Akinci, H. M. Albers, M. Armstrong, A. Banerjee, K. Blaum, C. Brandau, B. A. Brown, C. G. Bruno, J. J. Carroll, X. Chen, C. J. Chiara, M. L. Cortes, S. F. Dellmann, I. Dillmann, D. Dmytriiev, O. Forstner, H. Geissel, J. Glorius, A. Goergen, M. Gorska, C. J. Griffin, A. Gumberidze, S. Harayama, R. Hess, N. Hubbard, K. E. Ide, Ph. R. John, R. Joseph, B. Jurado, D. Kalaydjieva, Kanika, F. G. Kondev, P. Koseoglou, G. Kosir, Ch. Kozhuharov, I. Kulikov, G. Leckenby, B. Lorenz, J. Marsh, A. Mistry, A. Ozawa, N. Pietralla, Zs. Podolyak, M. Polettini, M. Sguazzin, R. S. Sidhu, M. Steck, Th. Stoehlker, J. A. Swartz, J. Vesic, P. M. Walker, T. Yamaguchi, and R. Zidarova, "Measurement of the isolated nuclear two-photon decay in ^{72}Ge," Phys. Rev. Lett. **133**, 022502 (2024).

G. Hudson-Chang, S. Naimi, Y. Abe, R. Crane, H. F. Li, T. Moriguchi, M. Mukai, D. Nagae, A. Ozawa, S. Suzuki, T. Uesaka, T. Yamaguchi, Y. Yamaguchi, and A. Yano, "Development of a low energy loss micro-channel plate based position-sensitive detector for the Rare Radio-Isotope Ring," Nucl. Instrum. Methods Phys. Res. A **1069**, 169980 (2024).

Y. Abe, Y. Yamaguchi, M. Wakasugi, H. Baba, T. Fujinawa, Z. Ge, A. Goto, S. Michimasa, H. Miura, T. Moriguchi, D. Nagae, S. Naimi, J. Ohnishi, S. Omika, S. Ota, A. Ozawa, F. Suzaki, H. Suzuki, S. Suzuki, N. Tadano, A. Tokuchi, T. Uesaka, K. Wakayama, T. Yamaguchi, and Y. Yano, "Performance of a precise isochronous magnetic field over a wide momentum range in the Rare-RI Ring," Nucl. Instrum. Methods Phys. Res. A **1072**, 170083 (2025).

Presentations

[International Conferences/Workshops]

T. Yamaguchi (invited), "RI beam experiments with fragment separator and storage ring," International Workshop on Nuclear Physics Related to HIAF, Huizhou, China, April 16–19, 2024.

K. Tsukada (invited), "Present status and future prospects of SCRIT electron scattering facility," Merger of the Poznan Meeting on Lasers and Trapping Devices in Atomic Nuclei Research and the International Conference on Laser Probing (PLATAN2024), Jyvaskyla, Finland, June 9–14, 2024.

K. Tsukada (oral), "Present status and future prospect of the SCRIT electron scattering facility," The 12th International Conference on Direct Reactions with Exotic Beams (DREB2024), Wiesbaden, Germany, June 24–28, 2024.

K, Tsukada (oral), "Recent results and prospects of the SCRIT electron scattering facility," 14th International Conference on Nucleus-Nucleus Collisions (NN2024), Whistlar, Canada, August 19–24, 2024.

M. Wakasugi (invited), "SCRIT facility and first electron scattering off online-produced radioactive nuclei," The 15th International Symposium on Electron Beam Ion Sources and Traps (EBIST2024), Kielce, Poland, August 27–30, 2024.

R. Ogawara (oral), "Ion-trapping properties of SCRIT: Charge state and spatial distributions of ^{132}Xe ions," The 15th International Symposium on Electron Beam Ion Sources and Traps (EBIST2024), Kielce, Poland, August 27–30, 2024.

T. Ohnishi (invited), "Present status and perspective of the SCRIT electron scattering facility," International Symposium on Nuclear Science (ISNS-24), Sofia, Bulgaria, September 9–13, 2024.

M. Wakasugi (invited), "First electron scattering off online-produced ^{137}Cs and prospect for ^{132}Sn, Low-Energy Electron Scattering for Nucleon and Exotic Nuclei," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

S. Iimura (invited), "Development of a high-flux MRTOF isobar separator for beam purification," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

T. Ohnishi (invited), "Present status and perspective of the ISOL system, ERIS, at the SCRIT electron scattering facility," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

Y. Kikuchi (poster), "Evaluation of momentum and angular dispersion of ^{208}Pb ion trapped on SCRIT using ion analyzer simulation," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

R. Ogawara (poster), "Ion-trapping properties of SCRIT: Effects of electron beam conditions," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

Y. Maeda (poster), "The upgrade of accelerating cavity of SR2 for eliminating beam instability," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

H. Matsubara (poster), "MRTOF simulation for optimal isobar separation between ^{132}Sn and ^{132}Sb," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

M. Tachibana (poster), "Development of position detector for luminosity monitor in SCRIT experiment," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

R. Teraguchi (poster), "Cooling efficiency of MRTOF bunchers," Low-Energy Electron Scattering for Nucleon and Exotic Nuclei (LEES2024), Sendai, Japan, October 28–November 1, 2024.

T. Yamaguchi (invited), "Rare RI Ring Facility Experiments with stored rare isotopes," RIKEN-IMP Symposium, Wako, Japan, November 7–8, 2024.

T. Yamaguchi (invited), "Present and future of the Rare-RI Ring facility at RIBF," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

T. Moriguchi (oral), "Improvements of time-of-flight detector utilizing a thin foil and crossed static electric and magnetic fields," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

Y. Yamaguchi (oral), "Recent developments at the Rare-RI Ring facility," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

A. Yano (oral), "Improvemnet of transmission efficiency of the Rare-RI Ring with vertical steering magnets," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

G. Hudson-Chang (poster), "A position-sensitive Schottky cavity detector for increased mass accuracy at the Rare RI Ring," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

T. Yamaguchi (poster), "In-ring detector developments for the Rare-RI Ring Facility," 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.

T. Yamaguchi (invited), "Status and future of R3," Collaboration Meeting Nuclear Astrophysics with Storage Rings (NUCAR), Darmstadt, Germany, December 2–4, 2024.

M. Watanabe (poster), "Current status of SCRIT facility for electron scattering measurement of short-lived nuclei," The 2nd International African Symposium on Exotic Nuclei (IASEN2024), Cape town, South Africa, December 9–13, 2024.

T. Yamaguchi (invited), "Rare RI Ring Facility: tool of precision mass spectrometry of short-lived nuclei," DPG The German Physical Society, Colonge, Germany, March 10–14, 2025.

[Domestic Conferences/Workshops]

山野翼 (口頭発表), 「SCRIT 標的におけるトラップイオンのダイナミクス」, 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 18 日–3 月 21 日.

小川原亮 (口頭発表), 「新たな実験領域を切り開くためのビームリサイクル技術の開発」, 2024 年度創発の場, 東京都 (L stay& grow), 2024 年 6 月 26–6 月 27 日.

小川原亮 (口頭発表), 「新たな実験領域を切り開くためのビームリサイクル技術の開発」, 第 3 回融合の場, 京都市 (京都大学百周年記念ホール), 2024 年 7 月 18–7 月 19 日.

小川原亮 (ポスター), 「ビームリサイクル用蓄積リング α-KSR のデザイン」, 第 21 回日本加速器学会年会, 山形市 (山形テルサ), 2024 年 7 月 31 日–8 月 3 日.

小川原亮 (口頭発表), 「SCRIT における ^{132}Xe の価数と空間分布の時間発展」, 日本物理学会第 79 回年次大会, 札幌市 (北海道大学), 2024 年 9 月 16 日–9 月 19 日.

立花万梨子 (口頭発表), 「SCRIT 実験におけるルミノシティモニター用位置検出器の開発」, 日本物理学会第 79 回年次大会, 札幌市 (北海道大学), 2024 年 9 月 16 日–9 月 19 日.

山口貴之 (招待講演), 「蓄積リングによる高エネルギービーム多価イオン状態の原子核の崩壊」, 日本物理学会第 79 回年次大会, 札幌市 (北海道大学), 2024 年 9 月 16 日–9 月 19 日.

山口貴之 (招待講演), "Experiments of highly charged ions stored in ESR," 第 2 回「新しいスキンを考える会」京都市 (京都大学), 2024 年 11 月 14 日.

小河原亮 (招待講演), 「SCRIT 施設の今後の展望」, 第 13 回停止・低速 RI ビームを用いた核分光研究会, 福岡市, 九州大学, 2025 年 2 月 20 日–2 月 21 日.

滝浦一樹 (口頭発表), 「稀少 RI リングのための新規共鳴型 Schottky 検出器のオンライン性能評価」, 日本物理学会 2025 年春季大会, オンライン, 2025 年 3 月 18 日–3 月 21 日.

菊池悠太 (口頭発表), 「SCRIT における標的イオンの捕獲中平均運動エネルギーの評価」, 日本物理学会 2025 年春季大会, オンライン, 2025 年 3 月 18 日–3 月 21 日.

西澤悟 (口頭発表), 「U-238 ビームの核破砕反応で生成した医療用 α 線源 Ac-225 の生成断面積測定」, 日本物理学会 2025 年春季大会, オンライン, 2025 年 3 月 18 日–3 月 21 日.

Award

G. Hudson-Chang, “A position-sensitive Schottky cavity detector for increased mass accuracy at the Rare RI Ring,” Best Poster Prize, 11th International Conference on Nuclear Physics at Storage Rings (STORI24), Huizhou, China, November 18–22, 2024.