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. We published the results of the world's first electron scattering experiment with online-produced radioactive isotopes in 2023. This result is a milestone for the SCRIT project, and it will also be considered to lead the unstable nuclear research to the next stage. An upgrade of the electron beam power that drives RI beam production is currently underway. 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 2023, we replaced capacitors of the kicker-magnet system and confirmed the long-time operation. In addition, two steerer magnets were made to correct for vertical beam misalignment. 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 instrumentations 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) Rear 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 generation technology (SCRIT), beam cooling and stopping 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.

After long development, in 2022, we successfully performed the world's first electron scattering experiment with online-produced unstable nuclei, which is ^{137}Cs. In 2023, we published the results in Physical Review Letters (K. Tsukada *et al*., Phys. Rev. Lett. **131**, 092502 (2023)), and issued a press release. This is a milestone of the SCRIT project, and it is also considered to open new possibilities in unstable nuclear research. In addition, electron scattering experiments with Xe isotopes have been conducted to investigate the isotope dependence of nuclear structure precisely. The angular distributions of ^{130,132,134,136}Xe isotopes have been already measured, and, in 2023, we measured those of ^{124,126,128}Xe isotopes at the electron beam energy of 150 MeV. Remained data will be measured soon.

Next stage in the SCRIT project is electron scattering off short-lived unstable nuclei. The first goal is ^{132}Sn, which is a symbolic nucleus on unstable nuclear research due to the double magic number ($Z = 50$, $N = 82$). Several upgrades are underway to achieve this goal. Main upgrade is to increase electron beam power for the supply of high intensity RI beam. Other upgrades are the improvement of the electron beam stability in the storage ring, the development of new monitor system to investigate the ion motion inside the SCRIT device, and the development of the isobar selection device. These upgrades are being made with the goal of completion within a few years.

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. The Schottky pick-up successfully monitored a single $^{78}Kr^{36+}$ ion circulation with the measurement time of less than 10 milliseconds in the first commissioning experiment.

We conducted several mass measurements for neutron rich nucleus far from stability. After the careful analysis, the mass of ^{123}Pd was determined precisely and its effect on heavy element synthesis was investigated with collaborators. We concluded that the composition around ^{123}Pd observed in the solar system can only be reproduced using the new mass values, and published a paper in early 2022. The final mass values of other measured nuclei, such as Ni-isotopes, will be determined soon.

The insulation breakdown of a ceramic capacitor used as the charging circuit of the kicker system, which occurred frequently during the experiment conducted in November 2021, significantly affected the progress of the experiment. We investigated the cause of the problem, but found no external factors, and considered the problem to be the capacitor itself. It was difficult to determine the exact cause due to so severe damage, but it was found that the central part of the three-layer structure was particularly damaged inside the molded resin. Therefore, we decided to use a single-layer capacitor to avoid overheating of the central part. Owing to the evaluation of the comparison between the old and new capacitors, all old capacitors in the kicker magnet were replaced in 2023, and the offline long-time operation was successfully conducted. In addition, the improvement of the injection efficiency is one of the important improvements. One reason of the low injection efficiency into R3 is the vertical misalignment of RI beam. Therefore, we constructed new steer magnets and we will install these magnets in the SHARAQ-OEDO beam line. Furthermore, to investigate the profile of the injected beam precisely, new monitor detectors, two PPACs, were installed inside the kicker magnet's chamber. The information obtained from the monitor system will be useful for the evaluation of the beam optics of the injection.

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 2022, we developed the prototype devices for EDC and ADC devices, and further improvements of EDC and ADC are ongoing. In 2023, we proceeded the development of the simulation code based on the analytical model to investigate the dynamics for RUNBA. This simulation code helps us to predict the beam dynamics in the storage ring. Furthermore, we tested and maintained several RF devices required in RUNBA.

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List of Publications & Presentations

Publications

[Original Papers]

K. Tsukada, Y. Abe, A. Enokizono, T. Goke, M. Hara, Y. Honda, T. Hori, S. Ichikawa, Y. Ito, K. Kurita, C. Legris, Y. Maehara, T. Ohnishi, R. Ogawara, T. Suda, T. Tamae, M. Wakasugi, M. Watanabe, and H. Wauke, "First observation of electron scattering from online-produced radioactive target," Phys. Rev. Lett. **131**, 092502 (2023).

K. Nasyedkin, M. Watanabe, and K. Kono, "Anomalous temperature dependence of energy levels of electrons on helim," Low Temp. Phys. **49**, 955–960 (2023).

[Review Articles]

S. Naimi, Y. Yamaguchi, T. Yamaguchi, and A. Ozawa, "Recent achievements at the Rare-RI Ring, a unique mass spectrometer at the RIBF/RIKEN," Eur. Phys. J. A **59**, 90 (2023).

[Proceedings]

R. Ogawara, Y. Abe, T. Ohnishi, A. Enokizono, M. Hara, T. Hori, S. Ichikawa, K. Kurita, Y. Maehara, T. Suda, K. Tsukada, M. Wakasugi, M. Watanabe, and H. Wauke, "Ion-trapping properties of SCRIT: Time evolutions of ^{138}Ba charge state distributions," Nucl. Instrum. Methods Phys. Res. B **541**, 90 (2023).

T. Ohnishi, D. Abe, Y. Abe, R. Danjyo, A. Enokizono, T. Goke, M. Hara, Y. Honda, T. Hori, S. Ichikawa, S. Iimura, Y. Ishikura, K. Ishizaki, Y. Ito, K. Kurita, C. Legris, Y. Maehara, Y. Nagano, R. Obara, R. Ogawara, T. Suda, T. Tamae, K. Tsukada, M. Wakasugi, M. Watanabe, H. Wauke, T. Yamano, and S. Yoshida, "The SCRIT electron scattering facility at RIKEN RI Beam Factory," Nucl. Instrum. Methods Phys. Res. B **541**, 380 (2023).

Presentations

[International Conferences/Workshops]

K. Tsukada (oral), "Present status and future prospect of the SCRIT electron scattering facility," The 4th International Conference on Advances in Radioactive Isotope Science (ARIS2023), Avignon, France, June 4–9, 2023.

T. Yamaguchi (oral), "Storage ring facilities for radioactive ions new detectors and upgrade plans," The 4th International Conference on Advances in Radioactive Isotope Science (ARIS2023), Avignon, France, June 4–9, 2023.

T. Yamaguchi (invited), "Challenge to exotic nuclei-Rare RI storage ring facility at RIBF," The 3rd International Workshop on "Origin of Elements and Cosmic Evolution: From Big-Bang to Supernovae and Mergers" (OECE2023), Beihang University, China, November 1–3, 2023.

Y. Abe (invited), "Present status and upgrade plan of RI production target in SCRIT electron scattering facility," 8th High Power Targetry Workshop, Wako, Japan, November 6–10, 2023.

T. Yamaguchi (invited), "Present status of the storage-ring mass spectrometer at RIBF," International Symposium on Stored Ions for Precision Measurement, Shanghai (Fudan University), China, November 22–24, 2023.

K. Tsukada (invited), "Present status of the SCRIT electron scattering facility," Annual Meeting of JSPS/NRF/NSFC A3 Foresight Program "Nuclear Physics in the 21st Century," Xi'an, China, December 1–9, 2023.

Y. Yamaguchi (invited), "R3 isomer beam filter (R3IBF)," Advancing physics at next RIBF (ADRIB24), Wako, Japan, January 23–24, 2024.

T. Yamaguchi (poster), "New physics opportunities at the Rare-RI Ring facility," British-German WE-HEraeus-Seminar Nuclear Astrophysics with Ion Storage Rings, Had Honnef, Germany, January 29–February 02, 2024.

[Domestic Conferences/Workshops]

大西哲哉 (ポスター発表), 「理化学研究所 RI ビームファクトリーにおける SCRIT 電子散乱施設の現状」, 日本加速器学会第 20 回年次大会, 船橋市 (日本大学), 2023 年 8 月 29 日–9 月 1 日.

小川原亮 (ポスター発表), 「ビームリサイクル技術における蓄積粒子のダイナミクス解析」, 日本加速器学会第 20 回年次大会, 船橋市 (日本大学), 2023 年 8 月 29 日–9 月 1 日.

阿部康志 (招待講演), 「SCRIT の現状とこれから」, 第 12 回停止・低速 RI ビームを用いた核分光研究会 (12th SSRI), 豊島区 (立教大学), 2023 年 9 月 5–6 日.

小川原亮 (招待講演), 「稀少不安定核実験のためのビームリサイクル技術の開発進捗」, 第 12 回停止・低速 RI ビームを用いた核分光研究会 (12th SSRI), 豊島区 (立教大学), 2023 年 9 月 5–6 日.

矢野朝陽 (招待講演), 「垂直ステアリング磁石導入による稀少 RI リングのアップグレード」, 日本量子医科学会第 3 回学術大会, 和光市, 2023 年 12 月 8–9 日.

T. Yamano (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 18–21 日.

[Seminars]

大西哲哉, 「理研 RI ビームファクトリーにおける不安定核研究」, 埼玉大学現代物理学の展開, 浦和市 (埼玉大学), 2023 年 6 月 14 日.

大西哲哉, 「RIBF における元素合成解明に向けた大型実験装置の現状」, 2023 年度 第 1 回宇宙史研究センター構成員会議, つくば市 (筑波大学), 2023 年 6 月 27 日.

渡邊正満, 「不安定原子核の大きさを測定する」, 豊橋市 (豊橋技術科学大学), 2023 年 11 月 27 日.

Press Release

大西哲哉, 若杉昌徳, 須田利美, 栗田和好, 塚田暁, 「世界初のオンライン生成不安定原子標的を用いた電子散乱の成功」, 理化学研究所プレスリリース, 2023 年 9 月 1 日, https://www.riken.jp/press/2023/20230901_1/index.html .

Award

大西哲哉, 若杉昌徳, 須田利美, 栗田和好, 塚田暁, 「世界初のオンライン生成不安定原子標的を用いた電子散乱の成功」, 2023 年度理研栄峰賞, 2024 年 3 月 12 日.

Outreach Activity

阿部康志, 渡邊正満, 「原子核サイエンス最前線」, 仁科加速器科学研究センター, 2023 年 4 月 30 日.