Research Facility Development Division
Instrumentation Development Group
Rare RI-ring Team

1. Abstract

The aim of Rare-RI Ring (R3) is to measure the masses of short-lived unstable nuclei far from the beta-stability line. In particular, a high-precision mass measurement for nuclei located around the *r*-process path (rare-RI) is required in nucleosynthesis point of view. Through the commissioning experiments by 2017, we confirmed the high ability of R3 as a storage ring capable of handling one event, and demonstrated that it is possible to perform the time-of-flight Isochronous Mass Spectrometry (IMS) in shorter than 1 millisecond. In 2018, we performed mass measurement experiments for the first time. In 2020, the kicker system was modified to flatten the magnetic field distribution, and the performance study using unstable nuclei was successfully conducted. In 2021, we performed mass measurement experiments using the upgraded kicker system. The results of the experiment dispelled concerns about the results of the previous experiment that the injection angle might greatly affected the accuracy of the mass determination. On the other hand, a failure occurred in the kicker power supply that interfered with the progress of experiments. The cause of the failure was investigated and resolved in this fiscal year. We have plan to conduct a beam test to confirm the stable operation of the kicker system before resuming the mass measurement experiments.

2. Major Research Subjects

(1) Further improvement of mass measurement efficiency and precision
(2) Precision mass measurement for rarely produced isotopes related to *r*-process

3. Summary of Research Activity

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 also confirmed that it is useful for fine tuning of the isochronous field.

We performed mass measurement in the third commissioning experiment by using unstable nuclei which masses are well-known. The masses of ^{79}As, ^{77}Ga, ^{76}Zn, and ^{75}Cu relative to ^{78}Ge were deduced with the accuracy of several ppm. In addition, we have improved the extraction efficiency to 2% by considering the matching condition between the emittance of injection events and the acceptance of R3 in the fourth commissioning experiment. This extraction efficiency was sufficient to conduct the accepted two proposals: mass measurements of Ni isotopes and south-west region of ^{132}Sn.

In November 2018, we conducted the first experiment using R3 to measure the masses for ^{74,76}Ni in 4 days. After that, we also measured the masses for ^{122}Rh, ^{123,124}Pd, and ^{125}Ag in 4.5 days. These nuclei were successfully extracted from R3 with the efficiency of 1–2%. However, unexpected deviation from the evaluated values of literature remained in the masses obtained by detailed analysis. This was thought to be due to the following two reasons. One is that due to the kicker field distribution is not flattened, the injection angle is different between the reference and target nucleus, and therefore the relative value of TOF is incorrect. The other is that the absolute value of beta or magnetic rigidity determined for each extracted event is incorrect.

In 2020, we modified the kicker system to flatten the magnetic field distribution as well as to dispel the concerns of the results of first experiment. As a result of performance study using unstable nuclei, we succeeded in forming the kicker field with 100 ns flat-top for injection and long flat-top of 350 ns or more for extraction. The experimental efficiency had been improved by a factor of two or more than previous condition because all nuclides can be extracted at once thanks to the long flat-top.

Using this upgraded kicker system, we measured the mass for ^{74}Ni again in April 2021. Although the kicker field distribution was flattened, the results of masses were the same as those of the first experiment. In other words, concerns about the effects of differences in injection angles have been dispelled. As a subsequent analysis, it was clarified that the reason is the second concern described above. Recently, 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. A five-days continuous test was conducted in November 2022 to compare the old and new capacitors. As a result, the old capacitor failed again while the new capacitor was fine. We will replace all the capacitors and conduct a performance test of the kicker system in 2023.

Members

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List of Publications & Presentations

Publications

[Original Papers]

H. F. Li, S. Naimi, T. M. Sprouse, M. R. Mumpower, Y. Abe, Y. Yamaguchi, D. Nagae, F. Suzaki, M .Wakasugi, H. Arakawa, W. B. Dou, D. Hamakawa, S. Hosoi, Y. Inada, D. Kajiki, T. Kobayashi, M .Sakaue, Y. Yokoda, T. Yamaguchi, R. Kagesawa, D. Kamioka, T. Moriguchi, M. Mukai, A. Ozawa, S. Ota, N. Kitamura, S. Masuoka, S. Michimasa, H. Baba, N. Fukuda, Y. Shimizu, H. Suzuki, H. Takeda, D. S. Ahn, M. Wang, C. Y. Fu, Q. Wang, S. Suzuki, Z. Ge, Yu. A. Litvinov, G. Lorusso, P. M. Walker, Zs. Podolyak, and T. Uesaka, "First application of mass measurements with the Rare-RI Ring Reveals the solar *r*-process abundance at A = 122 and A = 123," Phys. Rev. Lett. **128**, 152701 (2022).

ナイミ・サラ, リ・ホンフー, 山口由高, 上坂友洋, 「元素起源の謎解明に向けた超高速質量測定法の実現」, Isotope News **785**, 32 (2023).

Presentations

[Domestic Conferences/Workshops]

山口貴之 (招待講演), 「多価イオンビームによる 2 光子稀崩壊の観測」, 新学術領域研究「宇宙観測検出器と量子ビームの出会い. 新たな応用への架け橋」, 領域研究会, オンライン, 2022 年 5 月 20–21 日.

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神田真矩 (口頭発表), 「稀少 RI リングのためのプラスチックシンチレータと WLS ファイバーを用いた位置検出器の開発」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

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佐々木健太 (口頭発表), 「稀少 RI リングのためのシンチレーションファイバーを用いた位置検出器の開発」, 日本物理学会 2023 年秋季大会, オンライン, 2023 年 3 月 15–19 日.

Press Release

「元素起源の謎の解明に向けた世界最速質量測定が始動—稀少 RI リングを用いた短寿命放射性同位体の質量測定に成功—」, 理化学研究所, 筑波大学, 埼玉大学, 東京大学, 2022 年 4 月 28 日.