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A recoil mass separator for nuclear astrophysics experiments

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Abstract

A recoil mass separator was constructed for experiments of nuclear astrophysics using radioactive nuclear beams, and its performance was tested. The observed beam suppression factor around $M \sim 20$ was 10^{-4} when the system was tuned for $\Delta M = 1$ heavier ions than beam ions. With a charge state breeding technique, it became 10^{-8} when the system was tuned for $\Delta q = +1$ larger ions than beam ions.

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Keywords: Recoil mass separator; Nuclear astrophysics; Beam suppression

A radioactive nuclear beam facility [1] was constructed and experiments using radioactive nuclear beams currently available have been carried out. This facility, whose driving machine is the $K = 68$ SF cyclotron, consists of two kinds of target ion sources (an ECR ion source and a surface ionization ion source), a high resolution isotope separator,

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a 60 m beam transport line [2], and a linac complex, by which radioactive nuclear ions with a charge to mass ratio of $q/A > 1/30$ are accelerated up to 1.05 MeV/u [3].

One of the scientific interests using radioactive nuclear beams is an investigation of the nucleosynthesis in the universe. Especially we have tried to study rapid proton (rp-) process in the explosive hydrogen burning. Along this theme, several experiments have been prepared.

A recoil mass separator was constructed for the investigation of the nuclear reaction rates under the astrophysical temperature. There are two reasons why it is necessary for such measurements.

(1) In the case where reaction rates of nuclear reactions, for examples, (p, γ) and (α, γ) are relatively small, the required beam intensity becomes $10^8 \sim 10^{10}$ pps. For measurements of the reaction rates, recoil nuclei from the nuclear reactions have to be detected with little background radiation events. In order to avoid the background caused by the radioactive nuclear beam itself, the recoil nuclei and the radioactive nuclear beam should be separated. A recoil mass separator is suitable to suppress the radioactive nuclear beam at its focal plane detector.

(2) In the case where the reaction rates of nuclear reactions, for example, $(\mathrm{p}, \mathrm{p}')$, (α, p), and (α, n) are relatively large, the required beam intensity becomes $10^3 \sim 10^5$ pps, and measurements of their reaction rates can be performed by directly driving the radioactive nuclear beam into a detector system. For carrying out these measurements, it is necessary to prepare pure radioactive nuclear beams without the contamination of stable nuclei. A recoil mass separator plays an important role to suppress the contribution of these contaminant stable nuclear species.

We have tested the performance of a recoil mass separator for the above two reasons. For the reason (1), several factors relating to the beam suppression was investigated. This investigation was performed with $^{19}\mathrm{Ne}(\mathrm{p}, \gamma)$ reaction. For the reason (2), stable nuclear beams could be suppressed by a charge state breeding using the recoil mass separator as a beam transport line. In practice, this method was tested with $^{18}\mathrm{Ne}(\mathrm{p}, \mathrm{p}')$ reaction.

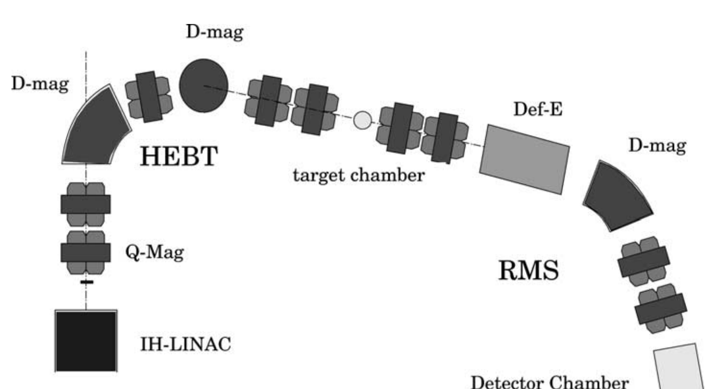

Fig. 1. The ion optical configuration from the linac to a detector system. At the downstream of a target chamber, there is a recoil mass separator.

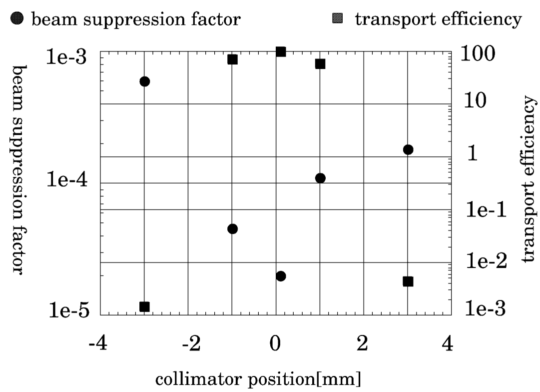

Fig. 2. The measured beam suppression factor with $^{20}Ne^{7+}$ beam. The horizontal axis shows the vertical position of the 4 mm ∅ collimator at the target chamber. RMS was tuned for $\Delta M = 1$ heavier ions than the beam.

We briefly describe the results of the performance test of a recoil mass separator (see Fig. 1). The ion optical configuration from the linac to a target chamber is QQDQDQQ. At the downstream of the target chamber, there is a recoil mass separator (RMS), whose configuration is QQEDQ, where Q, D and E stand for the quadrupole, dipole magnets, and electric dipole, respectively.

As the first nuclear astrophysics experiment, we planned the measurement of the resonance strength at the 2.64 MeV level in ^{20}Na by the $^{19}Ne(p,\gamma)\,^{20}Na$ reaction. This experiment would require a relatively high radioactive nuclear beam intensity. The intensity of ^{19}Ne radioactive beam was expected to be the order of 10^8 pps at the target position. The required beam suppression factor had to be at least the order of 10^{-4}. But, at the first measurement using the ^{20}Ne stable nuclear beam, the beam suppression factor was 10^{-3}.

In order to improve the beam suppression factor, the ray-trace simulation was carried out. From its result, two origins of this beam suppression were conjectured. One was that ^{19}Ne beams might collide with the top- and bottom-walls in the vacuum chamber of the dipole magnet. Another was that the beams with lower charge states might collide with the electric electrode plate in the electric deflector.

To discuss these origins individually, ^{20}Ne beams with different charge states were provided. At the target chamber, a collimator having a 4 mm ∅ aperture was set to an ideal beam spot. ^{20}Ne ions were detected at the entrance of RMS by a Faraday cup, and were detected at the focal point of RMS by a position sensitive silicon detector.

For the determination of the contribution to the beam suppression factor by the first suspected source, the vertical position of the 4 mm ∅ collimator was changed by 1 mm steps, and ^{20} Ne^{7+} ions were measured at the entrance and the focal point of RMS under the optical condition for $A/q = 21/7^+$. The result is shown in Fig. 2. It shows that the ideal beam suppression factor becomes 10^{-5} and if the vertical beam position is 3 mm lower than the center, it becomes near 10^{-3}.

For the determination of the contribution to the beam suppression factor by the second suspected source, the beam suppression factors were measured individually with the ^{20}Ne having different charge states 4^+ to 8^+ under the ion-optical condition for $A/q = 20/7^+$.

As the result, the beams whose charge state were lower than 4^+ collided with the electric electrode, But their suppression factor were enough smaller than 2×10^{-6}.

From these facts mentioned above, it was turned out that the main contribution to the beam suppression factor was the beam colliding with the top- and bottom-walls in the dipole magnet. So, two additional steering magnets and more beam monitors were constructed and the vertical position of the ion optical elements were adjusted again. As the result, the beam suppression factor of RMS itself became 1×10^{-4}.

The other astrophysical experiment planned is to search for the resonance level of ^{19}Na by $^{18}\mathrm{Ne(p, p')}$ reaction. In this case, the required beam intensity would be 10^3 pps, since the ^{18}Ne beam would be directly transported to a detector system including a gas target.

The ^{18}Ne beam intensity had become 10^5 pps and contaminant ^{18}O stable nuclear beam had become a few nA at the exit of the ISOL. We planned to separate $^{18}\mathrm{Ne}^{9+}$ from ^{18}O whose maximum charge state was 8^+ by utilizing the ion optical elements to the end of the RMS as a A/q separation. The ions beams with $A/q = 18/2^+$ were accelerated up to 1.05 MeV/u. After passing through a thin carbon foil ($= 10\ \mu\mathrm{g/cm}^2$) at the exit of the linac, the ions with $A/q = 18/9^+$ were analyzed by the HEBT (see Fig. 1) and the RMS.

The measured beam suppression factor of ^{18}O was 1×10^{-8}. As the final result, ^{18}Ne beam intensity was 3×10^3 pps at the detector position of the RMS and the maximum yield ratio of contaminant ^{18}O ions to ^{18}Ne became 1.5%.

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