Experimental studies of the two-step scheme with an intense radioactive $^{132}$Sn beam for next-generation production of very neutron-rich nuclei

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The usefulness of a two-step scheme with a $^{132}$Sn beam proposed1 for the efficient production of mid-heavy very-neutron-rich RIs was investigated, as an alternate method for the in-flight fission of a $^{238}$U beam (one-step scheme). The two-step scheme is a combination of an isotope-separation online (ISOL) system with a thick U target and a high-intensity proton beam as the first step, and the projectile fragmentation of re-accelerated RI beams (e.g., $^{132}$Sn) as the second step. We measured production cross sections beyond $^{125}$Pd, up to which the cross sections had already been measured at GSI together with the neighboring RIs,2) to evaluate the yields of RIs using the two-step scheme with a $^{132}$Sn beam. The 278-MeV/nucleon $^{132}$Sn beam was supplied from BigRIPS, and the very neutron-rich RIs around the neutron number $N = 82$ were produced in the ZeroDegree spectrometer with a 5.97-mm Be target. Yields obtained by the two-step and one-step schemes were estimated based on the measured cross sections, and we examined whether and to what extent the two-step scheme at future 1-MW beam facilities can reach further into the neutron-rich region.

Figure 1 shows the production yields of Pd isotopes obtained using the two-step scheme with a $^{132}$Sn beam and the one-step scheme with 1-MW beam powers. The two-step yields ($Y_{2\text{step}}$) decrease more slowly with neutron numbers than the one-step yields ($Y_{1\text{step}}$), and $Y_{2\text{step}}$ becomes larger than $Y_{1\text{step}}$ beyond $^{124}$Pd. The ratio of $Y_{2\text{step}}/Y_{1\text{step}}$ around the $N = 82$ region is shown in Fig. 2. This ratio systematically increases, as moving away from the stability line. Thus, the two-step scheme is more favorable than the one-step scheme to yield more neutron-rich region beyond our results, especially for the region of the supernova $r$-process path. The calculated $Y_{2\text{step}}$ with a cross-section formula COFRA4) indicated by black lines reproduces the experimental results well.

ISOL systems can provide various RIs over the nuclear chart; thus, a wide region of very neutron-rich RI beams can be produced by the two-step scheme. By using the ISOLDE yield database3) and the cross-section formula COFRA, the $Y_{2\text{step}}$ in the whole region was estimated. The $Y_{2\text{step}}$ was expected to be larger than the $Y_{1\text{step}}$ around the neutron-rich $N = 50, 60, 82$, and 90, including the supernova $r$-process path. The two-step scheme is considered a powerful tool to open a new window into the unknown region of mid-mass to heavy, very neutron-rich nuclei.

Fig. 1. Yield comparison between the two-step scheme with a $^{132}$Sn beam (orange circles) and the one-step in-flight fission of a $^{238}$U beam (blue squares) for Pd isotopes.

Fig. 2. Ratios of the $Y_{2\text{step}}$ with a $^{132}$Sn beam to the $Y_{1\text{step}}$. Orange and blue regions indicate that the two- and one-step schemes are more useful than the other, respectively. Dark-blue square dots represent the supernova $r$-process path.

References

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