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

H. Suzuki,[*1] K. Yoshida,[*1] N. Fukuda,[*1] H. Takeda,[*1] Y. Shimizu,[*1] D. S. Ahn,[*1] T. Sumikama,[*1] N. Inabe,[*1] T. Komatsubara,[*1] H. Sato,[*1] Z. Korkulu,[*1] K. Kusaka,[*1] Y. Yanagisawa,[*1] M. Ohtake,[*1] H. Ueno,[*1] T. Kubo,[*1] S. Michimasa,[*2] N. Kitamura,[*2] K. Kawata,[*2] N. Imai,[*2] O. B. Tarasov,[*3,*1] D. P. Bazin,[*3,*1] J. Nolen,[*4,*1] and W. F. Henning[*4,*5,*1]

The usefulness of a two-step scheme with a ^{132}Sn beam proposed[1)] 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

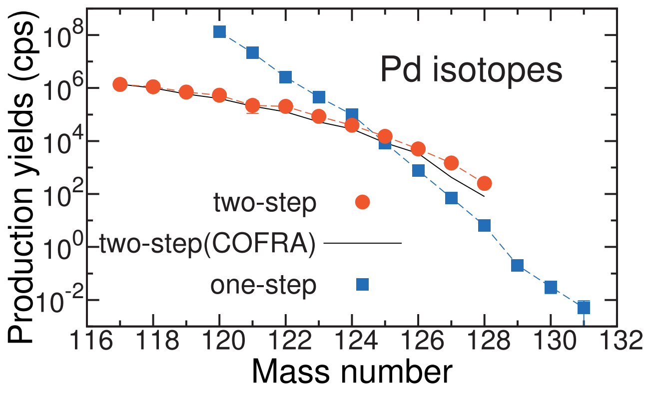

Fig. 1. Yield comparison between the two-step scheme with a ^{132}Sn beam (orange circles) and the one-step in-flight fission of a ^{238}U beam (blue squares) for Pd isotopes.

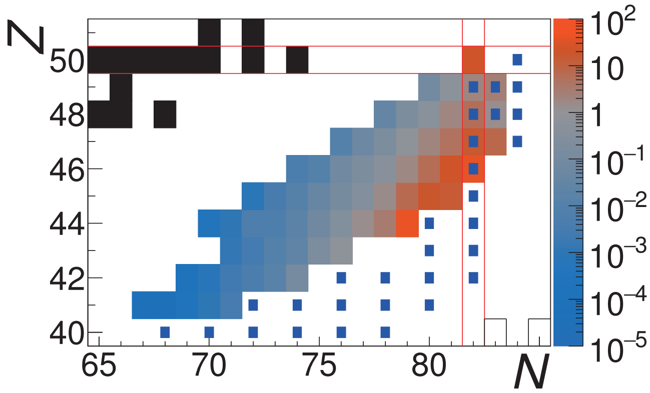

Fig. 2. Ratios of the Y_{2step} with a ^{132}Sn beam to the Y_{1step}. Orange and blue regions indicate that the two- and one-step schemes are more useful than the other, respectively. Dark-blue square dots represent the supernova *r*-process path.

and the one-step scheme with 1-MW beam powers. The two-step yields (Y_{2step}) decrease more slowly with neutron numbers than the one-step yields (Y_{1step}), and Y_{2step} becomes larger than Y_{1step} beyond ^{124}Pd. The ratio of Y_{2step}/Y_{1step} 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_{2step} with a cross-section formula COFRA[4)] 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 database[3)] and the cross-section formula COFRA, the Y_{2step} in the whole region was estimated. The Y_{2step} was expected to be larger than the Y_{1step} 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.

† Condensed from the article in Phys. Rev. C **102**, 064615 (2020)

*1 RIKEN Nishina Center
*2 Center for Nuclear Study, University of Tokyo
*3 National Superconducting Cyclotron Laboratory, Michigan State University
*4 Division of Physics, Argonne National Laboratory
*5 Physik Department, Technische Universität München

References
1) K. Helariutta *et al.*, Eur. Phys. J. A **17**, 181 (2003).
2) D. Pérez-Loureiro *et al.*, Phys. Lett. B **703**, 552 (2011).
3) ISOLDE Yield Database web page, `http://isoyields-classic.web.cern.ch`.
4) COFRA web page, `http://www.usc.es/genp/cofra`.