Production cross sections of ^{225}Ac and ^{225}Ra in the ^{232}Th(^{14}N, $xnyp$) reactions at 56, 79, and 98 MeV/nucleon

X. Yin,[*1] A. Nambu,[*1] S. Oshikiri,[*1,*2] K. Suzuki,[*1,*2] A. Hino,[*2] and H. Haba[*1]

^{225}Ac ($T_{1/2}$ = 10.0 d) is one of the most promising alpha-particle-emitting radionuclides for targeted radionuclide therapy.[1)] Its precursor, ^{225}Ra ($T_{1/2}$ = 14.9 d), is useful to generate high-purity ^{225}Ac. Thus, proton-induced reactions on ^{232}Th to form ^{225}Ac and ^{225}Ra have been well investigated.[2)] Proton beams up to 210 MeV are available for ^{225}Ac production from RRC.

In 1991, Ambe *et al.*[3)] proposed the production of radionuclides of a large number of elements (multitracer) by the spallation of metallic targets such as ^{nat}Cu, ^{nat}Ag, and ^{197}Au irradiated with a 135-MeV/nucleon ^{14}N (or ^{12}C, ^{16}O) beam from RRC. With this ^{14}N beam, ^{225}Ac and ^{225}Ra can be produced in the ^{232}Th(^{14}N, $xnyp$)^{225}Ac, ^{225}Ra reactions.[4)] The cross sections are essential to verify the feasibility of the ^{232}Th(^{14}N, $xnyp$)^{225}Ac, ^{225}Ra reactions for practical productions of ^{225}Ac and ^{225}Ra with RRC. In our previous paper,[4)] we reported the cross sections of the ^{232}Th(^{14}N, $xnyp$)^{225}Ac, ^{225}Ra reactions at 116 and 132 MeV/nucleon. In this work, the cross sections at lower energies of 56, 79, and 98 MeV/nucleon were measured to evaluate the production yields of ^{225}Ac and ^{225}Ra more reliably.

The target consisted of three assemblies of three metallic ^{232}Th foils, each with a thickness of 69 mg/cm^2 and size of 12.5 × 12.5 mm^2. Two aluminum disks, each with a thickness of 370 mg/cm^2 and diameter of 15 mm, were interleaved between the thorium assemblies as beam energy degraders. The target was placed in a multitracer production chamber.[5)] A 100.1-MeV/nucleon ^{14}N^{7+} beam was extracted from RRC. The target was irradiated for 2 h with an 18-particle nA intensity. After irradiation, the middle ^{232}Th foils in every assembly were subjected to γ-ray spectrometry to determine the cross sections of ^{225}Ac and ^{225}Ra. The beam energies on the measured ^{232}Th targets were calculated to be 98, 79, and 56 MeV/nucleon using the stopping power model in the LISE^{++} program.[6)] The cross sections of ^{225}Ac and ^{225}Ra were determined by fitting the 440-keV γ-ray intensity of ^{213}Bi ($T_{1/2}$ = 45.59 min) in their radioactive decay chain.[4)]

The cross sections of ^{225}Ac and ^{225}Ra obtained in this work are shown in Fig. 1, together with those at 116 and 132 MeV/nucleon in our previous work.[4)] The cross sections of ^{225}Ac are larger than those of ^{225}Ra by factors of 4.2–5.3 at 56–132 MeV/nucleon, respectively. The experimental results are compared with those calculated by the Particle and Heavy Ion Transport code System (PHITS).[7)] The PHITS code reproduces the cross sections of ^{225}Ac above 98 MeV/nucleon, while it underestimates those at the lower energies. The cross sections calculated for ^{225}Ra by the PHITS code are larger than the experimental ones. The calculated values increase with the beam energy, while the experimental ones are independent of the beam energy. In Fig. 2, production yields of ^{225}Ac by 135-MeV/nucleon ^{14}N beams are compared with those by 210-MeV proton beams.[2)] The yields of both reactions are comparable if we use a target with the same thickness in the range of 0.5–5 g/cm^2.

By assuming experimental conditions (incident beam energy: 132 MeV/nucleon; beam intensity: 1 particle μA; target thickness: 4.5 g/cm^2; irradiation time: 2 d), 165 MBq of ^{225}Ac can be produced at the end of bombardment via the ^{232}Th(^{14}N, $xnyp$)^{225}Ac reaction.

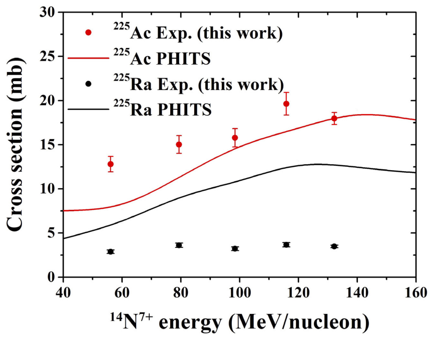

Fig. 1. Experimental and calculated excitation functions for the ^{232}Th(^{14}N, $xnyp$)^{225}Ac, ^{225}Ra reactions.

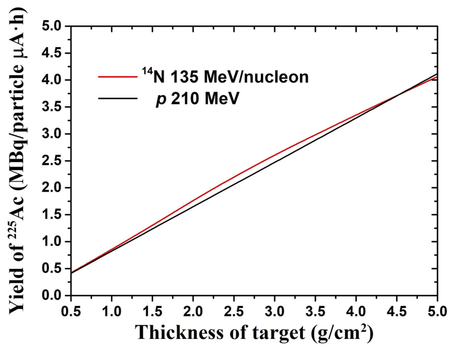

Fig. 2. Yields of 135-MeV/nucleon ^{14}N and 210-MeV proton beams on ^{232}Th targets with different thicknesses.

*1 RIKEN Nishina Center
*2 RI Research Department, FUJIFILM Toyama Chemical Co., Ltd.

References

1) M. Ferrier *et al.*, Radiochim. Acta **107**, 1065 (2019).
2) J. Weidner *et al.*, Appl. Radiat. Isot. **70**, 2602 (2012).
3) S. Ambe *et al.*, Anal. Sci. **7**, 317 (1991).
4) X. Yin *et al.*, RIKEN Accel. Prog. Rep. **54**, 162 (2021).
5) H. Haba *et al.*, Radiochim. Acta **93**, 539 (2005).
6) O. B. Tarasov, D. Bazin, LISE^{++} site, `https://lise.nscl.msu.edu/lise.html` .
7) Y. Iwamoto *et al.*, J. Nucl. Sci. Technol. **54**, 617 (2017).