Measurement of production cross sections of ^{175}Hf in the $^{\mathrm{nat}}$Lu(p,x) and $^{\mathrm{nat}}$Lu(d,x) reactions

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The chemical characterization of superheavy elements (SHEs) with atomic number ≤104 is one of the most important and challenging subjects in the field of nuclear chemistry. Prior to chemistry experiments on SHEs, it is important to find suitable chemical systems and experimental conditions using the no-carrier-added radiotracers of their lighter homologues. The long-lived Hf isotope, ^{175}Hf ($T_{1/2}$ = 70 d), is useful for basic studies on element 104, Rf. The ^{175}Hf isotope can be produced in proton- and deuteron-induced reactions on $^{\mathrm{nat}}$Lu. For efficient and quantitative production of this isotope, excitation functions are necessary to know. However, data are available only for the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction[1)] and not for the $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf. In this work, we measured the excitation functions for these reactions at RIKEN and the Institute for Nuclear Research (ATOMKI).

The excitation functions were measured using the stacked foil technique. At RIKEN, a target stack that consisted of 9 sets of a $^{\mathrm{nat}}$Lu foil (99% purity, 27.1 mg/cm^2 thickness), a $^{\mathrm{nat}}$Ta foil (99.95%, 17.0 mg/cm^2), and 2 $^{\mathrm{nat}}$Ti foils (≤99.6%, 4.4 mg/cm^2) was irradiated with a 14-MeV proton beam supplied from the RIKEN AVF cyclotron. Another target stack that consisted of 17 sets of a $^{\mathrm{nat}}$Lu foil (99%, 27.6 mg/cm^2), a $^{\mathrm{nat}}$Ta foil (99.95%, 17.1 mg/cm^2), and a $^{\mathrm{nat}}$Ti foil (≤99.6%, 4.4 mg/cm^2) was irradiated with a 24-MeV deuteron beam. At ATOMKI, a target stack that consisted of 17 sets of a $^{\mathrm{nat}}$Lu foil (99%, 20.7 mg/cm^2), a $^{\mathrm{nat}}$Ta foil (99.95%, 17.0 mg/cm^2), and 2 $^{\mathrm{nat}}$Ti foils (≤99.6%, 5.4 mg/cm^2) was irradiated with an 18-MeV proton beam from the MGC-20E cyclotron. Another target stack that consisted of 8 sets of a $^{\mathrm{nat}}$Lu foil (99%, 20.7 mg/cm^2) and a $^{\mathrm{nat}}$Ti foil (≤99.6%, 4.4 mg/cm^2) was irradiated with a 10-MeV deuteron beam. The $^{\mathrm{nat}}$Ta foils were used to determine the excitation functions for the $^{\mathrm{nat}}$Ta(p,x) and $^{\mathrm{nat}}$Ta(d,x) reactions. The $^{\mathrm{nat}}$Ti foils were used to confirm the beam energy and intensity based on the monitor reactions of $^{\mathrm{nat}}$Ti$(p,x)^{48}$V and $^{\mathrm{nat}}$Ti$(d,x)^{48}$V. All these target stacks were irradiated with 170–220 nA beam currents for 2 h. After the irradiation, each foil was subjected to γ-ray spectrometry with Ge detectors.

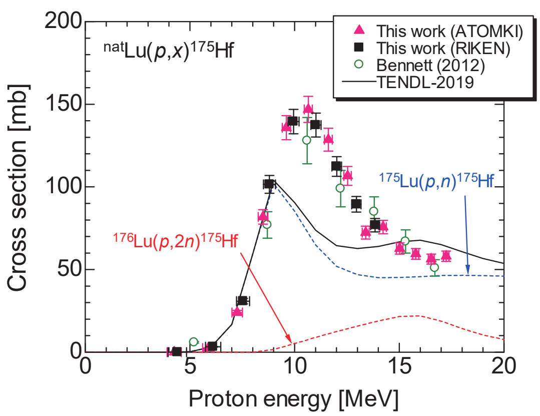

Fig. 1. Excitation function for the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction.

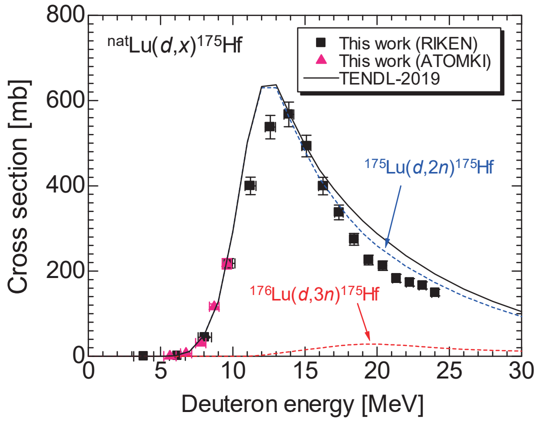

Fig. 2. Excitation function for the $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf reaction.

The excitation functions were measured for the $^{\mathrm{nat}}$Lu$(p,x)^{173,175}$Hf and $^{\mathrm{nat}}$Lu$(d,x)^{173,175}$Hf, ^{173,174m,174g,176m,177m,177g}Lu reactions. Figures 1 and 2 show the excitation functions for the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf and $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf reactions, respectively. For both reactions, our data measured at RIKEN and ATOMKI are consistent with each other. Data of the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction are also consistent with the data previously published by Bennet *et al.*[1)] Theoretically predicted cross sections for the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction in the TENDL-2019 library[2)] are lower than the experimental ones at 9–14 MeV. The peak energy of the excitation function in the TENDL-2019 is approximately 1.5 MeV lower than the experimental one. For the $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf reaction, TENDL-2019 slightly overestimates the cross sections at 10–14 MeV and above 15 MeV. The peak energy in TENDL-2019 is approximately 1 MeV lower than the experimental one. Physical thick-target yields of ^{175}Hf were deduced from the measured excitation functions. The yield of ^{175}Hf in the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction is 0.47 MBq/μA·h in the energy range of 4.2–17.2 MeV, while that in the $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf reaction is 2.0 MBq/μA·h in the range of 5.7–24.0 MeV. The yield of the $^{\mathrm{nat}}$Lu$(d,x)^{175}$Hf reaction is 4 times larger than that of the $^{\mathrm{nat}}$Lu$(p,x)^{175}$Hf reaction in the energy ranges investigated in this work.

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References

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