Measurement of isotopic production cross sections of proton- and deuteron-induced spallation reactions on ^{93}Zr at 200 MeV/nucleon

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Proton- and deuteron-induced spallation reactions are considered as the candidate processes for the transmutation of long-lived fission products (LLFPs). In our previous study on the proton- and deuteron-induced reactions on LLFP ^{93}Zr at 105 MeV/nucleon,[1] the isotopic production cross sections in few-nucleon removal channels were largely overestimated in the model calculations using PHITS.[2] To improve the reliability of the reaction model calculations, further systematic experimental data are required over a wide range of reaction energies. In this study, the isotopic production cross sections of the proton- and deuteron-induced spallation reactions on ^{93}Zr at 200 MeV/nucleon were measured in an inverse kinematics condition.

The experiment was conducted at the SAMURAI beamline[3] at RIBF. The secondary beam, including ^{93}Zr at 200 MeV/nucleon, was generated via inflight fission of ^{238}U and selected by using BigRIPS. The typical total rate of the beam was 5 kcps, and the purity of ^{93}Zr was 33%. Then, the beam bombarded a liquid hydrogen and a liquid deuterium target.[4] The reaction products were identified by using the SAMURAI spectrometer.[3] The isotopic production cross sections were derived from the number of incident ^{93}Zr beams and that of the generated isotopes.

The isotopic production cross sections of the proton- and deuteron-induced reactions on ^{93}Zr at 200 MeV/nucleon are shown in Fig. 1. The black circles and the red diamonds indicate the proton-induced cross sections (σ_p) and the deuteron-induced cross sections (σ_d), respectively. The error bars indicate only the statistical uncertainties.

Enhancement of the cross sections at ^{90}Zr and ^{89}Y, which have a neutron magic number $N = 50$, was observed as in the case of 105 MeV/nucleon measurement.[1] The effect of shell closure is still important in the interpretation of the spallation reaction cross sections at 200 MeV/nucleon, despite the high reaction energy compared to nucleon separation energies.

In Fig. 1, the experimental results are compared to the model calculations by using the particle and heavy-ion transport code system (PHITS) 2.82.[2] The spallation reactions have been well described as a two-step process composed of the formation of prefragments via

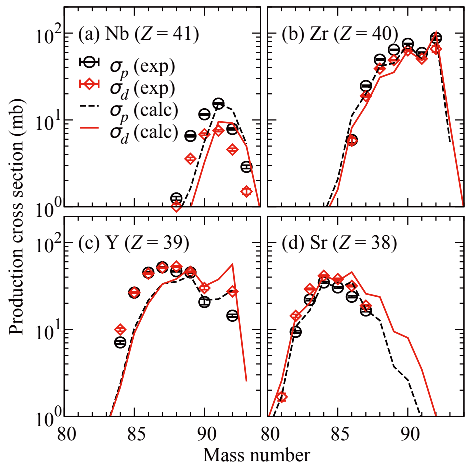

Fig. 1. Isotopic production cross sections of the proton- and deuteron-induced reactions on ^{93}Zr at 200 MeV/nucleon.

an intra-nuclear cascade process and the de-excitation process of the prefragments by evaporation of light particles. In this work, the Liège Intranuclear Cascade model (INCL 4.6)[5] and the generalized evaporation model (GEM)[6] were employed for these processes. The lines in Fig. 1 show the cross sections calculated by using PHITS. The black dashed line and the red solid line correspond to σ_p and σ_d, respectively.

The general behavior of the isotopic production cross sections are apparently well reproduced by the PHITS calculation; however, the mass-number distributions are shifted to heavier isotopes especially in proton-odd isotopes (Nb and Y). The production cross section of ^{92}Y is considerably overestimated in both the proton- and deuteron-induced cases. These can probably be understood by the poor reproduction of the excitation energy of reaction residue after the direct process, which is pointed out in Ref. 1). The models used in PHITS are expected to be improved in near future after close analyses of the spallation reaction data over a wide range of incident energies.

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