Cross section measurements in the reactions of ^{136}Xe on proton, deuteron and carbon at 168 MeV/u

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Abstract
The isotopic distribution of the production cross sections of ^{136}Xe on proton and carbon at 168 MeV/u were obtained in inverse kinematics technique at RIKEN Radioactive Isotope Beam Factory. The target dependence at 168 MeV/u was investigated systematically. The cross sections measured in the present work are compared with the previous results obtained at different reaction energies to investigate the energy dependence for the reactions on proton. The experimental results on proton are compared with the PHITS calculations including both the cascade and evaporation processes for the model benchmarking.

1 Introduction

Spallation and/or fragmentation reaction is a promising method for the production of the radioactive ion beams in flight [1]. Many experiments have been performed to study the reaction mechanisms of the spallation. The cross sections of the reaction products are important for the investigation. The isotopic production cross sections of ^{238}U + p at 1 GeV/u [2], ^{197}Au + p at 800 MeV/u [3], ^{208}Pb + p at 500 MeV/u [4] and 1 GeV/u [5] have been measured. In particular, the reaction of ^{136}Xe is studied systematically. Because the stable nuclei ^{136}Xe is usually used as a primary beam to generate neutron-rich nuclei by fragmentation or spallation reaction. The investigation of the target dependence and energy dependence is of great importance to optimize the beam production. The reaction of ^{136}Xe induced by proton at 200 MeV/u [6], 500 MeV/u [7] and 1 GeV/u [8] has been measured and the energy dependence on proton has been investigated. As for the reactions induced by other targets, such as deuteron- and carbon-induced reaction, the study is scarce. Only the reactions of ^{136}Xe + d at 500 MeV/u [9] and ^{136}Xe + Be [10] at 1 GeV/u are available.

In order to have a comprehensive understanding of the reaction mechanisms, we measured the isotopic cross sections of ^{136}Xe + p, ^{136}Xe + d and ^{136}Xe + C at 168 MeV/u by using the inverse kinematics technique. These data are helpful for the target dependence investigation. Together with the previous data measured at other reaction energies, the energy dependence would be studied. The isotopic production cross sections obtained from the experiment are expected to be helpful to understand the spallation reaction mechanisms and to benchmark the model calculations.

2 Experiment

The experiment was performed at RIKEN RIBF using the BigRIPS separator and ZeroDegree Spectrometer [11], operated by RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. The experimental setup is same as the one for ^{137}Cs [12]. The primary beam was ^{238}U at 345 MeV/u, with the intensity of 12 pnA. The secondary beams were produced by the in-flight fission of ^{238}U on a beryllium target located at the entrance of the BigRIPS. The total intensity of the secondary beams is about 8.5 $\times$ 10^3 particles per second (pps). Particles can be identified in BigRIPS separator event by event by using the TOF-$B\rho$-ΔE method [13]. The intensity of ^{136}Xe is 2.1 $\times$ 10^3 pps, with the purity of 24%.

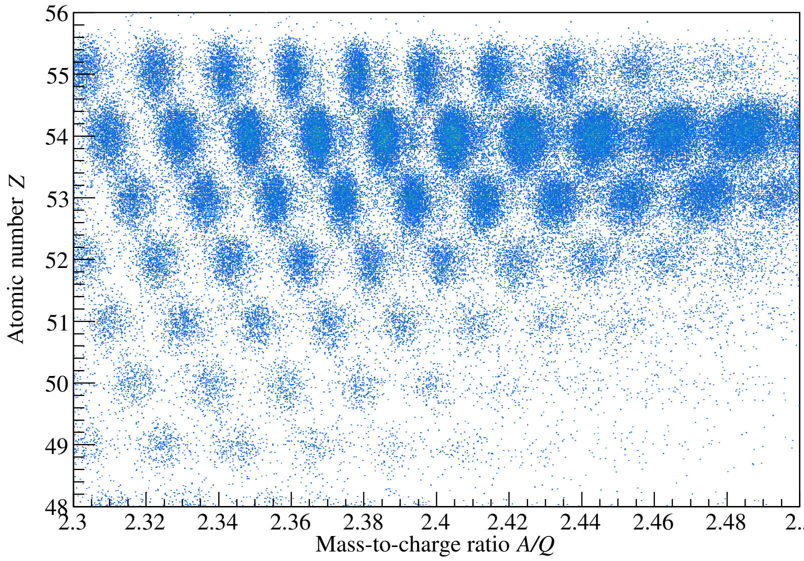

Fig. 1: Particle identification of Z versus A/Q analyzed by ZeroDegree Spectrometer for the reaction of ^{136}Xe on CH_2 target, with $B\rho$ -6% setting.

The inverse kinematics was adopted for the experiment. CH_2 (179.2 mg/cm^2), CD_2 (217.8 mg/cm^2) and carbon (226.0 mg/cm^2) targets were used to induce the secondary reactions. The energy of ^{136}Xe at the center of the secondary targets is 168 MeV/u. The data was also taken only use the target frame without target material (empty target run) in order to subtract the background contribution. The reaction products were measured and identified in the ZeroDegree Spectrometer unambiguously, using the similar method with BigRIPS. The time of flight (TOF) information was measured by the plastic scintillator. The magnetic rigidity ($B\rho$) was determined by the trajectory reconstruction using the position of particles measured by PPAC. The ionization chamber was used to measure the energy loss (ΔE). The atomic number Z and the mass-to-charge ratio A/Q were determined by the TOF-ΔE and $B\rho$-TOF correlations, respectively. The angular acceptance of the ZeroDegree Spectrometer is ± 45 mrad and ± 30 mrad in horizontal and vertical direction, respectively, and the momentum acceptance is $\pm 3\%$. In order to cover a wide range of the reaction products, 5 different $B\rho$ settings (+3%, 0%, -3%, -6%, -9%) were applied in the ZeroDegree Spectrometer. Fig. 1 shows the particle identification plot of the reaction products obtained from the ^{136}Xe beam on CH_2 target with $B\rho$ -6% setting. The typical A/Q and Z resolutions were 6.1 $\times 10^{-3}$ (FWHM) and 0.52 (FWHM), respectively. After the particles pass through the ZeroDegree Spectrometer, for the xenon isotopes, the ratio of the fully stripped ions ($Q = Z$) was about 67%.

3 Results and discussion

Fig. 2 shows the preliminary results of the isotopic production cross sections for ^{136}Xe on proton and carbon at 168 MeV/u. The statistical uncertainties were shown in the figure. The cross sections on carbon (σ_C) were obtained from the carbon target after subtracting the contribution from the beam-line material.

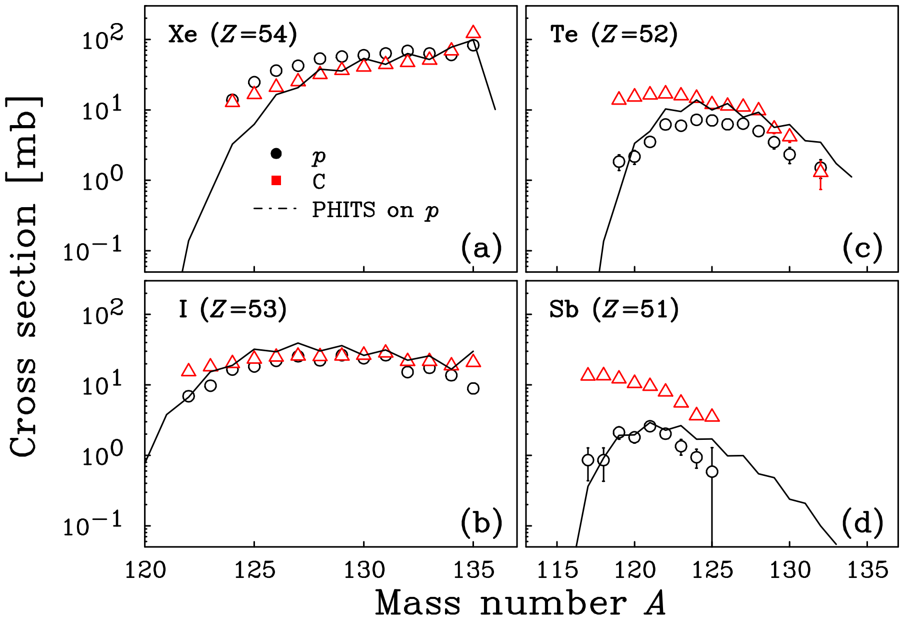

Fig. 2: Isotopic distribution of the cross sections for ^{136}Xe on proton (black dot) and carbon (red triangle) at 168 MeV/u. The black line represents the PHITS calculations on proton.

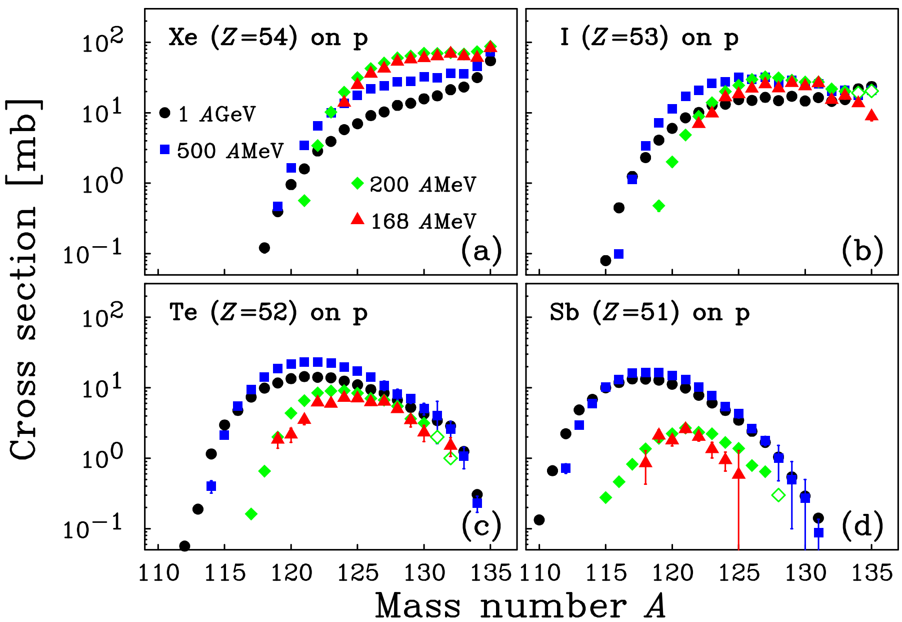

Fig. 3: Isotopic distribution of the production cross sections from element xenon ($Z = 54$) to antimony ($Z = 51$) for the reaction of ^{136}Xe + p at 168 MeV/u (red), 200 MeV/u (green), 500 MeV/u (blue) and 1 GeV/u (black). Empty diamonds at 200 MeV/u represent extrapolated value.

The cross sections on proton (σ_p) were obtained from CH_2 target after subtracting the contribution from carbon target and the beam-line material.

For the xenon and iodine isotopes in Fig. 2 (a) and (b), σ_p and σ_C looks similar, and the cross sections keep almost constant both on proton and carbon. For the tellurium and antimony isotopes, σ_C became larger than σ_p. These light products were produced by the central collision, the cross sections depend on the excitation energy of the pre-fragments. A relatively higher deposited energy of the pre-fragments in the carbon-induced reactions result in the higher cross sections.

The model calculations on proton target by Particle and Heavy Ion Transport system (PHITS) 2.76 [14] were shown in Fig. 2 to compare with the experimental results. The Intranuclear Cascade model of Liège (INCL) [15] and the generalized evaporation model (GEM) [16] were used for the cascade and evaporation processes, respectively. For the 4 elements shown in Fig. 2, PHITS calculations reproduce the overall tendency of the experimental results. While the overestimation in the neutron-rich side was observed. Such overestimation was also seen in the calculations of ^{93}Zr at 105 MeV/u [17] and ^{107}Pd at 118 MeV/u and 196 MeV/u [18]. Besides, the calculated cross sections by PHITS give a more obvious even-odd staggering than experimental results, which was also observed for the calculations of ^{137}Cs at 185 MeV/u [12] on proton.

The cross sections measured in the present work for the reaction of ^{136}Xe + p at 168 MeV/u were compared with the results obtained previously at different reaction energies in order to investigate the energy dependence. As shown in Fig. 3 for the comparison with the reactions at 200 MeV/u [6] (green) , 500 MeV/u [7] (blue), 1000 MeV/u [8] (black). For the xenon isotopes, the shape of the isotopic distribution is similar at different reaction energies, the value of the cross sections decrease as the reaction energy increase. For the tellurium and antimony isotopes, the cross sections at low reaction energies (168 MeV/u and 200 MeV/u) decreased rapidly, the cross sections at high reaction energy become larger, especially for the products in the neutron-deficient side. As discussed above, the cross sections of these light products depend on the excitation energy of the pre-fragment after the intranuclear cascade process, more energy deposited for the reaction at high reaction energy resulting in a larger cross sections.

4 Summary

The isotopic distribution of the cross sections for ^{136}Xe on proton and carbon at 168 MeV/u were obtained in inverse kinematics technique. The target dependence was investigated systematically. The cross sections of the light products are larger for the carbon-induced reaction because of the higher deposited energy. The cross sections on proton obtained in the present work were compared with the previous data measured at different reaction energies. It was found that for the xenon isotopes, the cross sections at low reaction energy are larger. The experimental results were compared with PHITS calculations, the overall tendency of the isotopic cross sections was reproduced. The overestimation in the neutron-rich side was observed. Such a comparison is expected to be helpful for the model benchmarking.

Acknowledgements

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