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Fragment mass and kinetic energy distributions from fission of light actinides

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Abstract

Fission fragment mass and kinetic energy distributions of the neutron-deficient light actinides ^{225}Pa and ^{227}Pa produced in the ^{16}O- and ^{18}O-induced reactions on ^{209}Bi with incident energies near the Coulomb barriers have been measured with a time-of-flight technique. Asymmetric mass division components are observed in both systems. Systematic features of symmetric and asymmetric mass divisions are discussed in terms of neutron number of fissioning nuclei.

1. Introduction

From the systematic studies on low energy fission of actinides [1–4], it has been verified that there are at least two independent deformation paths associated with symmetric and asymmetric mass divisions: two different fission barriers for each division leading to two kinds of scission configurations. According to the prediction of Möller [5], these deformation paths are affected by neutron shell structures of fissioning nuclei. It is expected that symmetric and asymmetric fission barrier heights will be equal at $N \approx 136$ in light actinides. Although an approach [6] has been made to confirm the asymmetric mass division component in light actinide region by using heavy-ion-induced reactions, no experimental evidence for asymmetric mass division was observed.

The aim of the present work is to search for asymmetric mass division components in heavy-ion-induced fission of neutron-deficient light actinides at incident energies near the Coulomb barriers with a time-of-flight (TOF) technique. In this report, measured fragment mass and kinetic energy distributions of the fission of ^{225}Pa ($N=134$) and ^{227}Pa ($N=136$) produced in the reactions ^{16}O+^{209}Bi and ^{18}O+^{209}Bi respectively are presented. It is systematically examined that how symmetric and asymmetric mass divisions are correlated with neutron number of fissioning nuclei.

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2. Experimental details

The experiments were carried out at the Japan Atomic Energy Research Institute tandem accelerator using beams of ^{16}O with energy of 86 MeV and ^{18}O with 85 MeV to bombard a ^{209}Bi (50 μg cm^{-2} thick) target evaporated onto a 10 μg cm^{-2} thick carbon foil. Fragment mass and kinetic energy distributions were measured with a TOF telescope as shown in Fig. 1. Each start (MCP1) and stop (MCP2) detector was composed

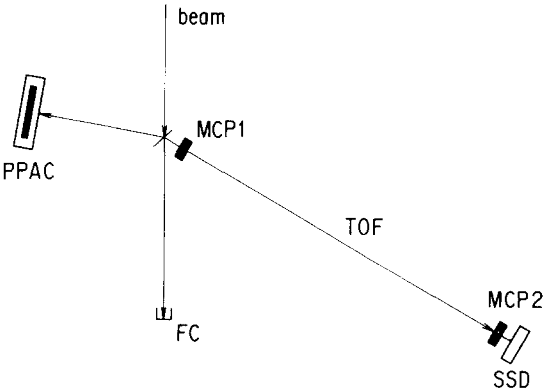

Fig. 1. Experimental set-up.

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of a carbon foil (30 μg cm^{-2} thick) and a microchannel plate. The flight path between MCP1 and MCP2 was about 100 cm. The energy signals were delivered with a 300 μg cm^{-2} thick Si surface barrier detector (SSD) located behind MCP2. The fragment mass A was determined from the flight time t and the kinetic energy E corrected for the pulse-height defect in a Si surface barrier detector; $A \propto Et^2$. To eliminate the contribution from the elastically scattered products in TOF-E spectra, complementary fragments were detected in coincidence with a position-sensitive parallel plate avalanche counter (PPAC) located about 35 cm from the target at the opposite side of the beam direction (Fig. 1).

The energy and time calibration was performed with elastically scattering ^{16}O and ^{18}O projectiles from a ^{209}Bi target. ^{127}I beams of energy 350 MeV were also used to bombard thin (50 μg cm^{-2}) calibration targets of ^{nat}Ag, ^{nat}In and ^{nat}Sb. The recoil nuclei and the scattered ^{127}I ions were detected with the present TOF system. An overall mass resolution of approximately 3.5 amu was achieved.

3. Results and discussion

Measured fragment mass distributions in the centre-of-mass system are shown in Figs. 2(a) and 2(b). Although the observed global mass distributions in each system are nearly symmetric, shoulders of asymmetric components are seen around mass numbers 90 and 135. Most probable total kinetic energy values were around 163 MeV for both systems and were about 6 MeV smaller than those expected from the empirical formula of Viola *et al.* [7].

Figure 2(c) shows the fragment mass distribution of the fissioning nucleus ^{233}Pa produced in the proton-induced reaction of ^{232}Th [8]. The distributions in Fig. 2 are obtained from the fission of Pa nuclei with same excitation energy E^* of 32 MeV, but different numbers of neutrons, ^{225}Pa ($N=134$), ^{227}Pa ($N=136$) and ^{233}Pa ($N=142$), and produced via different reaction systems. The full lines indicate the results of three-component gaussian analysis. The three-gaussian fit was carried out for the distribution of ^{233}Pa fission (Fig. 2(c)) by using nine free parameters; peak positions, peak values and widths for each of the three components. With an assumption that the widths of the symmetric mass division components are identical for the three reaction systems (full width at half-maximum (FWHM), 30.1 amu) because of the same excitation energy, the fitting procedures were applied to the present distributions (Figs. 2(a) and 2(b)) with the other eight free parameters. In fact, when we analyse the clear triple-humped mass distribution from the fission of ^{229}Th ($N=139$) produced in the ^{3}He$+^{226}$Ra reaction at $E^*=32.2$ MeV [9], the FWHM of the symmetric mass distribution is about 30.5 amu. Therefore, this assumption would be reasonable as a first approximation. From this analysis, the contribution of asymmetric components is about 10% for the neutron-deficient nuclei ^{225}Pa and ^{227}Pa, and about 60% for ^{233}Pa.

In Fig. 3, ratios of the probabilities for symmetric and asymmetric mass divisions are plotted as a function of neutron number of fissioning nuclei together with the data taken from ref. 10. The literature values are for an excitation energy of 6 MeV above asymmetric barriers ($E^*-B_f^a=6$ MeV). It is obvious that the symmetric mass division components decrease systematically with neutron number of fissioning nuclei; the feature reflects the variation in symmetric and asymmetric fission barrier heights as a function of neutron number of fissioning nuclei. As it is well known that excitation energy enhances the probability of symmetric mass division, the large value of the ^{233}Pa fission at $E^*=32$ MeV results from the increase in the excitation energy of the fissioning nucleus. The slopes of the exponential decrease between the data at $E^*=32$ MeV and those at 6 MeV are different. This means that the symmetric

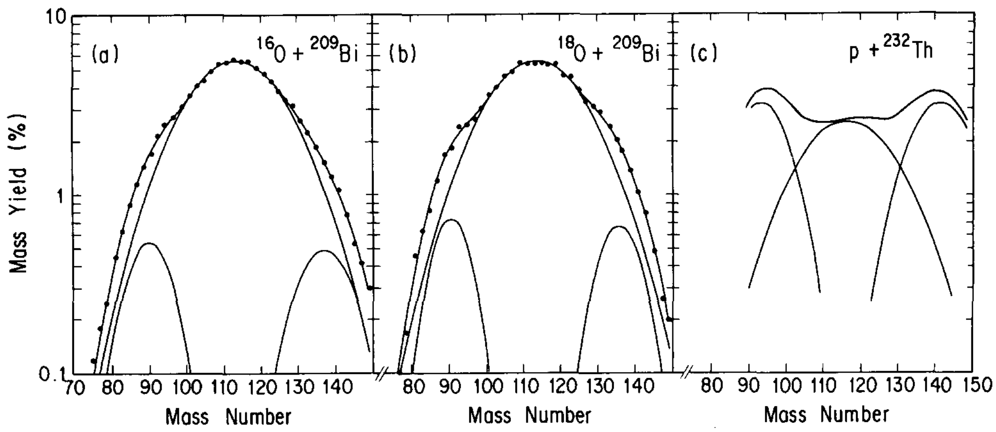

Fig. 2. Fragment mass distributions in the fission of (a) ^{225}Pa, (b) ^{227}Pa and (c) ^{233}Pa: ——, results of the three-gaussian fit.

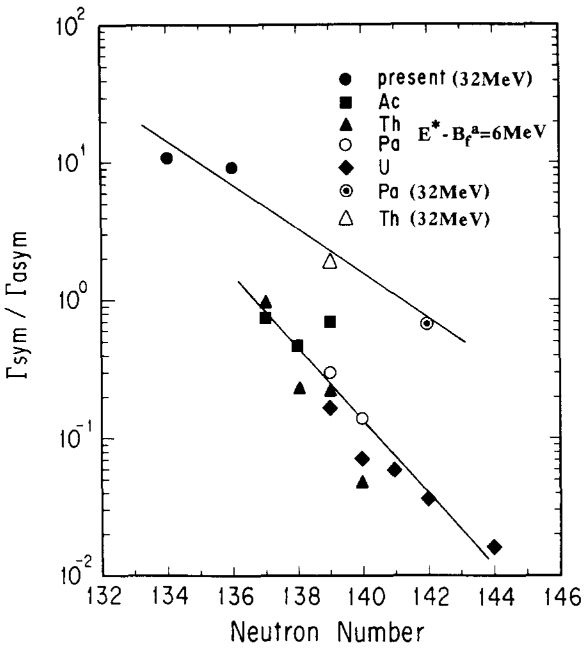

Fig. 3. Ratio of the probabilities for symmetric and asymmetric mass divisions as a function of neutron number of fissioning nuclei. The data are taken from refs. 8–10. ——, least-squares fit.

mass division in the neutron-deficient nuclei with $E^* = 32$ MeV seems to be suppressed. One reason is that level density at a symmetric fission barrier may become small compared with that at an asymmetric barrier in this neutron-deficient region. The other speculation is that different angular momenta are contributing to the formation of the fissioning nuclei; mean angular momentum $\langle J \rangle \approx 15\hbar$ for the present systems $^{16,18}O + {}^{209}Bi$ and $\langle J \rangle \approx 5\hbar$ for $p + {}^{232}Th$ [8]. Although the effect of angular momentum on both symmetric and asymmetric mass divisions is now an open question, the observed trend indicates that an angular momentum effect would enhance the asymmetric mass division.

In conclusion, we have confirmed the asymmetric mass division components in the fission of neutron-deficient light actinides. From the systematic treatment, it is found that the mass division strongly depends on neutron number of fissioning nuclei.

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