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Bimodal nature of actinide fission

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Abstract

Mass and kinetic energy distributions have been measured in the proton-induced fission of ^{232}Th and ^{238}U with two time-of-flight counter telescopes in coincidence. A binary structure was observed in the velocity and total kinetic energy distributions of fission fragments, with $A=128$–131 for ^{232}Th + p fission and $A=126$–130 for ^{238}U + p fission. From the present results, it is concluded that there are at least two kinds of scission configuration: elongated shapes probably associated with the symmetric path, and more compact shapes associated with the asymmetric path.

1. Introduction

Recent data for the total kinetic energy distributions in the spontaneous fission of heavy nuclides such as ^{258}Fm, ^{258}No, ^{259}Fm, ^{259}Md, ^{260}Md and ^{262}No have revealed the existence of two types of scission configuration for the same symmetric mass division [1]: a compact shape, corresponding to the observed high total kinetic energy of about 235 MeV, and an elongated shape, corresponding to a total kinetic energy of about 200 MeV. Hulet *et al.* [1] called such phenomena "bimodal" fission.

In the present work, to survey such a bimodal nature in light actinides, velocities and kinetic energies were measured with the double-arm time-of-flight (TOF) method, in the proton-induced fission of ^{232}Th + p [2] and ^{238}U + p. We investigated the two components in the time and kinetic energy distributions of fragments with the mass in the region of $A=126$–132, where both symmetric and asymmetric modes are expected.

2. Experimental details and data analysis

The target of ^{232}Th was evaporated on a 10 μg cm^{-2} carbon foil and the thickness of the target was estimated to be 45 μg cm^{-2}. The target of ^{238}U was electrodeposited on a 10 μg cm^{-2} nickel foil and the thickness was about 150 μg cm^{-2}. A beam of protons of energy 13 MeV from the JAERI tandem accelerator was used for the bombardment. The beam current was about 500 nA. The measurement of the velocities of the complementary fission fragments (binary fission fragments) was made with two TOF telescopes set up at 45° and −133.5° with respect to the beam direction, in order to take into consideration the kinematical deviation. The start and stop signals were picked up by means of a parallel plate avalanche counter (PPAC) and a microchannel plate (MCP) equipped with a 30 μg cm^{-2} carbon foil respectively. The flight paths were 82.0 cm and 60.7 cm with the detection solid angles of 0.1 msr and 2 msr respectively. The velocity calibration was performed with a time calibrator and a ^{252}Cf source whose average velocities of the light and heavy fragments have been accurately measured by many groups [3].

The primary mass (before neutron emission) of a fission fragment was obtained from the ratio of the two velocities of the pair fragments, with the assumptions that no neutron was emitted from the compound nucleus prior to fission, and that the neutrons from the primary fragment were isotropically emitted and did not alter the initial fragment velocity on average. The conservation of mass and linear momentum for the pre-neutron-emission fragments led to the equation

$$m_1^* = A(1+v_1^*/v_2^*)^{-1} \qquad (1)$$

where A denotes the mass of the fissioning nuclide, and v_1^* and v_2^* are the velocities of the pair in the

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center of the mass system (the asterisks mean pre-neutron-emission quantities). The kinetic energies of the fission fragments were easily calculated from the mass and velocity as

$$E_{KEi} = \left(\frac{1}{2}\right) m_i^* v_i^{*2} \qquad i=1, 2 \tag{2}$$

Before carrying out the above analysis, the TOF data were corrected for the velocity loss caused by the target material, the carbon foil of the MCP and the window of the PPAC, using the energy-loss relationship [4]. The resulting fragment mass resolution was estimated to be $\sigma(m) \approx 1.5$ u, mainly based on the resolution of the time measurement and the difference in the flight path depending on the emission angle.

3. Results and discussion

The average velocities of the light and the heavy fragments of the ^{232}Th+p fission were 1.46×10^9 cm s^{-1} and 1.01×10^9 cm s^{-1}, and those of the ^{238}U+p fission were 1.42×10^9 cm s^{-1} and 0.99×10^9 cm s^{-1}. To obtain the total kinetic energy (TKE) distribution as a function of the fragment mass, the complementary fragment kinetic energies were added. The overall average TKEs were 168.2 MeV and 174.3 MeV for ^{232}Th+p and ^{238}U+p, respectively, which is in agreement with the systematics of Viola *et al.* [5].

The quantitative features of the TKE distribution for each fragment mass were obtained as a function of the heavier fragment mass. The TKE of fragment masses $A=127$, 129 and 131 for ^{232}Th+p, and $A=126$, 128 and 130 for ^{238}U+p fission are shown in Figs. 1(a) and (b) respectively. It was found that the shapes of the distributions change systematically, and the distribution clearly has a shoulder at $A=129$–131 for ^{232}Th+p, while a shoulder is present in the mass region around $A=128$ for ^{238}U+p.

The observed TKE distributions were analysed, as a first approximation, by two Gaussians for the fragment masses $A=127$–133 for ^{232}Th+p and $A=125$–131 for ^{238}U+p fission. The peak positions and the area of each Gaussian were also estimated. For ^{232}Th+p fission, the peak positions of the two Gaussians were 169 MeV and 185 MeV for $A=128$. The average difference of the two peaks was about 16 MeV over the fragment mass region $A=128$–131. In contrast, the peak positions for $A=128$ in ^{238}U+p fission were 173 MeV and 188 MeV, so the difference was about 15 MeV over the region $A=126$–130.

The distance between two charge centers at scission as a function of the fragment mass in the system of ^{236}U fission has been calculated by Wilkins *et al.* [6] using the scission point model. The results are reproduced in Fig. 2, in which the region "A" shows the charge distance that gives rise to the maximum yield in each mass split.

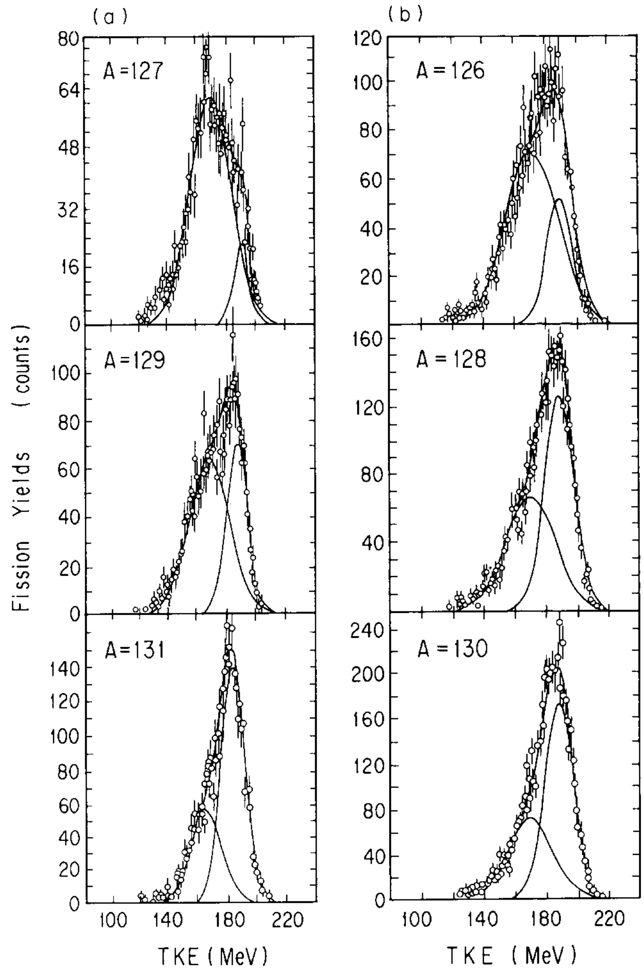

Fig. 1. (a) TKE distributions for the fragment masses $A=127$, 129 and 131 observed in ^{232}Th+p fission. Full curves indicate the result of a Gaussian fit to the energy distributions. (b) Same as (a) but for the fragment masses $A=126$, 128 and 130 in ^{238}U+p fission.

With the assumption that the total kinetic energy originates purely from the Coulombic repulsion between the two fragments at the scission point, the distance (D) between the two charge centers of the complementary fragments was evaluated for the peak energy of each Gaussian distribution for the fragment masses $A=128$, 130 and 132, and the results are plotted in Fig. 2 for ^{232}Th+p fission, represented by triangles: full triangles for the lower energy and open triangles for the higher energy. The error bars were estimated from the time resolution and the Gaussian fitting errors. The full circles in the figure show the distance calculated for the average TKE. (To avoid complexity, the results for ^{238}U+p are not shown in Fig. 2.)

It should be noted that the full triangles lie on the dashed straight line drawn through the full circles for

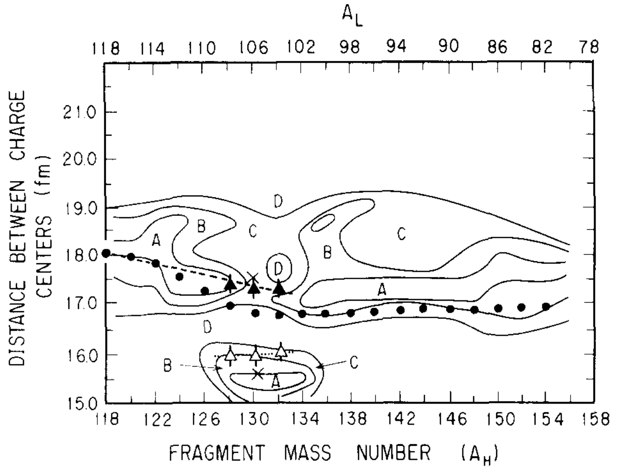

Fig. 2. Calculated distance between two charge centers for two complementary fragments at scission *vs.* fragment mass number in the system ^{236}U (taken from ref. 6). A, 75%–100% of maximum yield; B, 50%–75% of maximum yield; C, 25%–50% of maximum yield; D, 25% of maximum yield. The distance of the two charge centers at scission configuration is evaluated from the TKE of each fragment mass for $^{232}Th+p$ fission. The full circles show the distances calculated from the mean TKE distribution; open and full triangles indicate the distances corresponding to the two types of kinetic energy distribution (the error bars were estimated from the time resolution and the Gaussian fitting errors). The dashed line was extrapolated from the distances of the more symmetric region. The cross symbols are for the distances of the low and high kinetic energy components evaluated from the report on ^{258}Fm spontaneous fission (presented by Hulet *et al.* [1]).

the more symmetrically divided products. These components are probably associated with symmetric mass division. These trends of the distance between the two charge centers suggest the presence of at least two distinctively different scission configurations in the same mass division at around $A=127$–133: elongated shapes probably associated with more symmetric mass division, and compact shapes associated with asymmetric mass division. The compact shapes found in the mass region $A=127$–133 may be different from those expected from an extrapolation of more asymmetrically divided products. They may correspond to the high energy components, as seen in the spontaneous fission of ^{258}Fm.

It is also interesting to note that the trend of the most probable D values expected by Wilkins *et al.* [6] is in agreement with the present results shown in Fig. 2. Although, in the present work, the excitation energies of the compound nuclei are 16–18 MeV, the fragment shell effects at scission may not differ much from those calculated by Wilkins *et al.* Therefore, the presence of two kinds of D value for the same mass split in a particular fragment mass region is in agreement with the prediction obtained using the scission point model.

The distances between the two charge centers corresponding to the "bimodal fission" reported for the spontaneous fission of ^{258}Fm are also plotted by cross symbols in Fig. 2. Surprisingly, they lie close to the triangles of the present work, although the distance for a compact shape of the ^{258}Fm is smaller than that for $^{232}Th+P$ fission, possibly as a result of the $N=82$, $Z=50$ shell effect on both of the complementary fragments of ^{258}Fm. This similarity indicates that the "bimodal fission" is not a phenomenon peculiar to very heavy nuclides, such as ^{258}Fm and ^{260}Md, but that it is also observed in the low energy, proton-induced fission of ^{232}Th and ^{238}U.

4. Conclusions

In the proton-induced fission of ^{232}Th and ^{238}U, a binary structure was observed in the velocity and TKE distributions of fission fragments with $A=126$–131. From the present results, it is concluded that there are at least two kinds of scission configuration: elongated shapes probably associated with the symmetric path, and more compact shapes associated with the asymmetric path. The binary fission phenomena are present not only in the heavy actinides but also in the light actinide.

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