TERNARY FISSION OF $^{238}_{92}$U AND $^{232}_{90}$Th NUCLEI INDUCED BY 2.9 MeV NEUTRONS

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The ternary fission mechanism of $^{238}_{92}$U and $^{232}_{90}$Th induced by 2.9 MeV neutrons was investigated. Two modes of ternary fission of $^{239}_{92}$U have been determined.

The average total kinetic energy of fragments was found to be 174.5 MeV for ternary fission of $^{239}_{92}$U and 162 MeV for ternary fission of $^{232}_{90}$Th.

The frequency of occurence of ternary fission relative to binary fission was found to be 8×10^{-4} for fission of $^{238}_{92}$U induced by 2.9 MeV neutrons and 3×10^{-3} for fission of $^{232}_{90}$Th induced by 2.9 MeV neutrons.

Introduction

The existence of ternary fission od $^{238}_{92}$U and $^{232}_{90}$Th nuclei induced by 2.5 MeV neutrons was reported by Titterton [5] and Hill and Wheller [2]. The mechanism of ternary fission of $^{238}_{92}$U induced by thermal neutrons was investigated by Muga [3] and Benisz and Panek [1]. Muga suggested that two distinct modes of division are possible in ternary fission. In the work of Benisz and Panek two modes of ternary fission were determined. For the first mode the formation of a heavy fragment of similar mass as that for binary fission was observed. The third fragment is emitted from the light fragment of binary fission. For the second mode of ternary fission the simultaneous formation of three mass fragments was observed, each of them having a mass smaller than that of the heavy fragment of binary fission. For incident neutrons with energies higher then a fraction of eV the mechanism of ternary fission was not investigated.

In this paper investigation of the mechanism of ternary fission of $^{238}_{92}$U and $^{239}_{90}$Th induced by 2.9 MeV neutrons is described. Also the frequency of occurence of ternary fission relative to binary fission and the average kinetic energy release in ternary fission of $^{239}_{92}$U

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and $^{233}_{90}$Th were determined. Nuclear emulsion technique was used for the detection of ternary fission fragments. Nuclear plates were loaded with natural uranium and natural thorium. The abundance of $^{238}_{92}$U nuclei is about 99.3 per cent and that of $^{232}_{90}$Th nuclei 100 per cent.

Experimental procedure

Nuclear Ja-2 plates loaded with 1 per cent solution of uranyl nitrate and 2 per cent solution of thorium nitrate were applied for the detection of fragments of ternary fission. These plates were irradiated by 2.9 MeV neutrons from the $D(d, n)^3_2$He reaction. After irradiation the nuclear plates were developed by the temperature method in order to secure

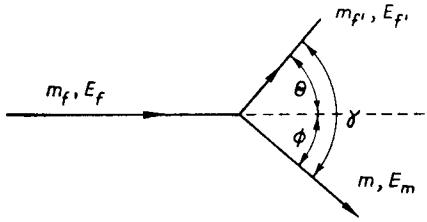

Fig. 1. Angular correlation

a good discrimination between α particles and fission fragments. The events were eliminated as false events when: *a*. the angle between two fragments was equal almost to 180 degrees, *b*. the total kinetic energy of fragments was smaller than 100 MeV, *c*. the following equations were fulfilled (1.1) and (1.2) (Fig. 1).

$$\frac{m_f}{m} = \cos \Phi + \frac{\sin 2\Phi}{\operatorname{tg} \theta}$$

$$\left(\frac{E_m}{E_{f'}}\right)_{\text{theor}} = \frac{4\, m_f/m}{(m_f/m - 1)^2} \cos^2 \gamma \tag{1.1}$$

$$0.7 \leqslant m_f/m \leqslant 2 \quad \text{and} \quad (E_m/E_{f'})_{\text{theor}} \approx (E_m/E_{f'}) \text{ exper} \tag{1.2}$$

where:

E_f, m_f — energy and mass of the binary fission fragment,
E_f — energy of the scattering binary fission fragment,
E_m, m — energy and mass of the recoil nucleus of Br or Ag,
θ — angle between the direction of the binary fission, fragment and the scattering binary fission fragment,
φ — angle between the recoil nucleus and the direction, of the binary fission fragment,
γ — angle between the recoil nucleus and the scattering binary fission fragment.

For example we have for ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons about 700 events for casses *a*, *b*, and *c*. A detailed description of measurement procedure and the procedure of the elimination of false ternary fission events have been elsewhere [1].

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89 events of ternary fission of $^{238}_{92}$U and 40 events of ternary fission of $^{232}_{90}$Th induced by 2.9 MeV neutrons were found in the present experiment.

The experimental results are presented in two types of graphs. Mass distributions for heavy, medium and light fragments for ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons

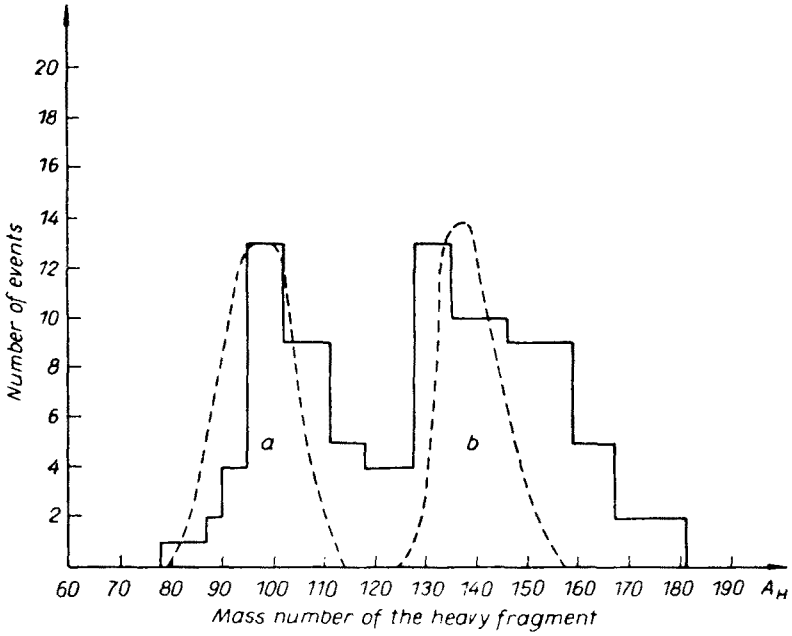

Fig. 2. Mass distribution of the heavy fragment in ternary fission of $^{238}_{29}$U + neutron. The dotted curve represents the corresponding mass distribution for binary fission as obtained in Ref. [4]

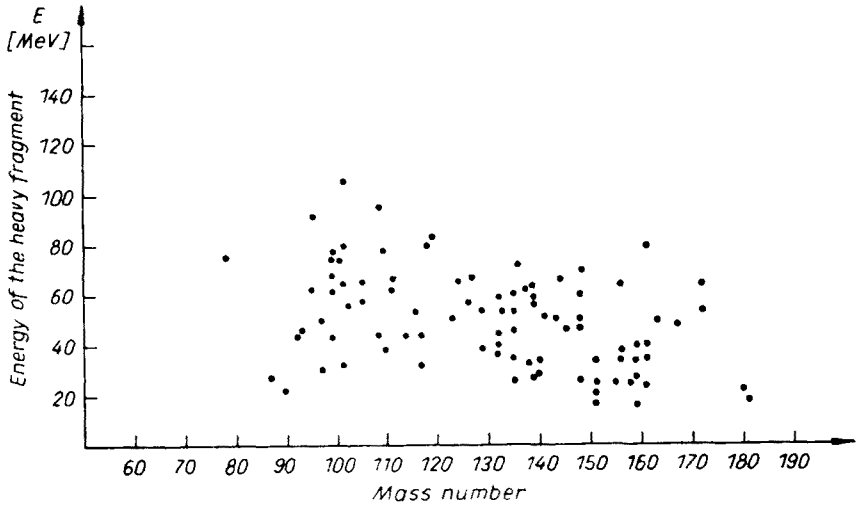

Fig. 3. Energy-mass correlation of the heavy fragment in ternary fission of $^{238}_{92}$U + neutron

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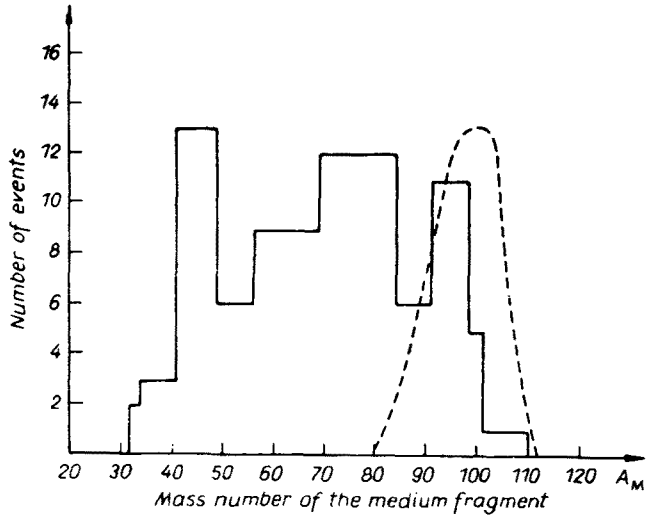

Fig. 4. Mass distribution of the medium fragment in ternaryfission of $^{238}_{92}U$ + neutron. The dotted curve represents the corresponding mass distribution for light binary fission as obtained in Ref. [4]

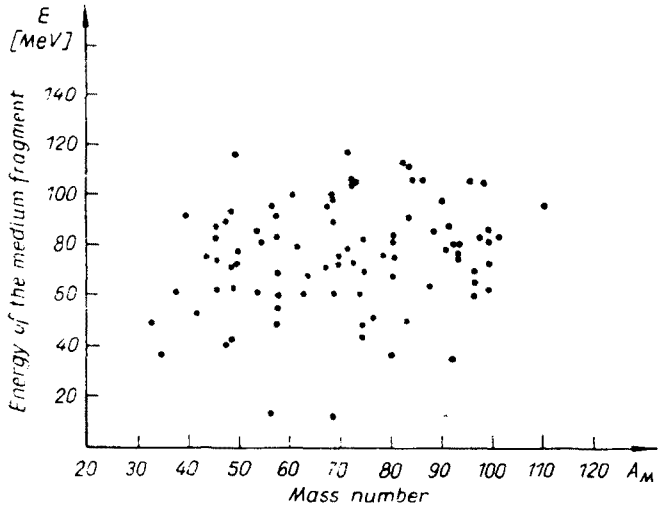

Fig. 5. Energy-mass correlation of the medium fragment in ternary fission of $^{238}_{92}U$ + neutron

are shown in Figs 2, 4, and 6. The same figures also show mass distributions for binary fission of $^{238}_{92}U$ induced by reactor neutrons (4). Figs 3, 5, and 7 show the energy-mass correlations. The mass distributions for the heavy fragment for ternary fission of $^{232}_{90}Th$ induced by 2.9 MeV neutrons and for binary fission fragments of the same isotope induced by reactor neutrons are shown in Fig. 8. Mass distributions for ternary fission (solid line) (Figs 2, 4, 8, 9 and 10) and mass distributions for binary fission (dotted line) are normalized

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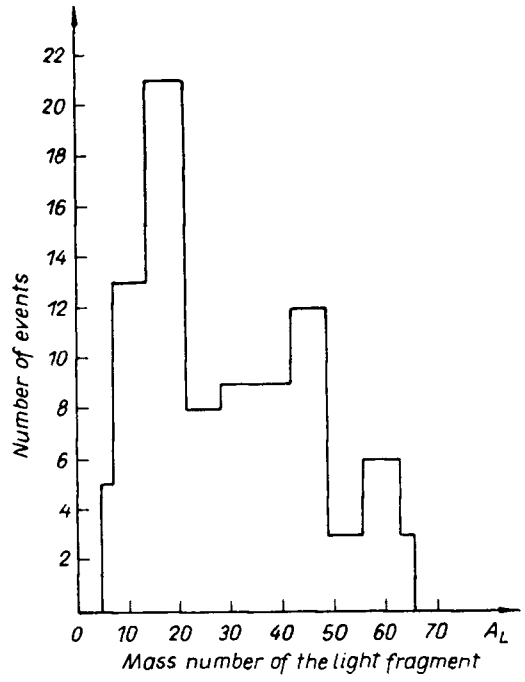

Fig. 6. Mass distribution of the light fragment in ternary fission of $^{238}_{92}U$ + neutron

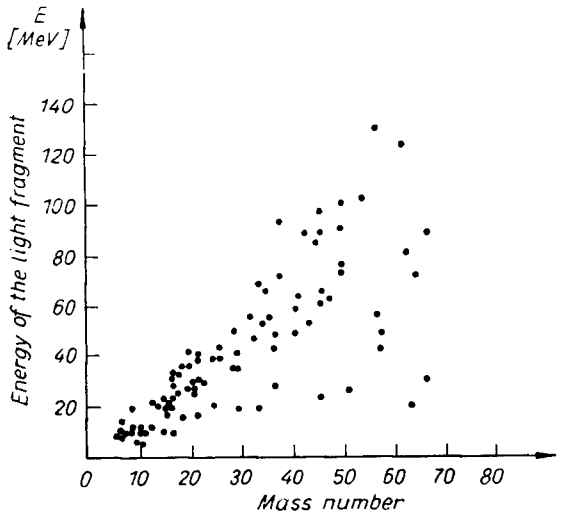

Fig. 7. Energy-mass correlation of the light fragment in ternary fission of $^{238}_{92}U$ +. neutron

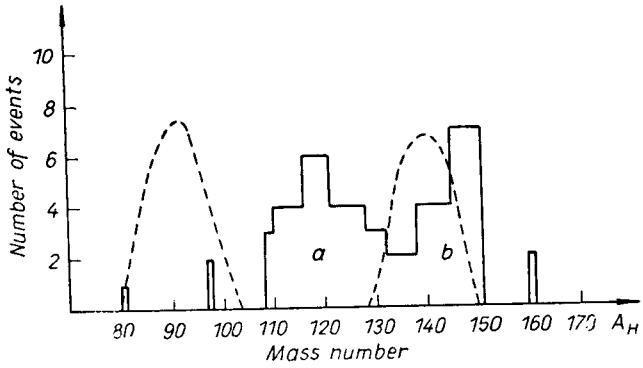

Fig. 8. Mass distribution of the heavy fragment in ternary fission of $^{232}_{90}$Th + neutron. The dotted curve represents the corresponding mass distribution for binary fission as obtained in Ref. [4]

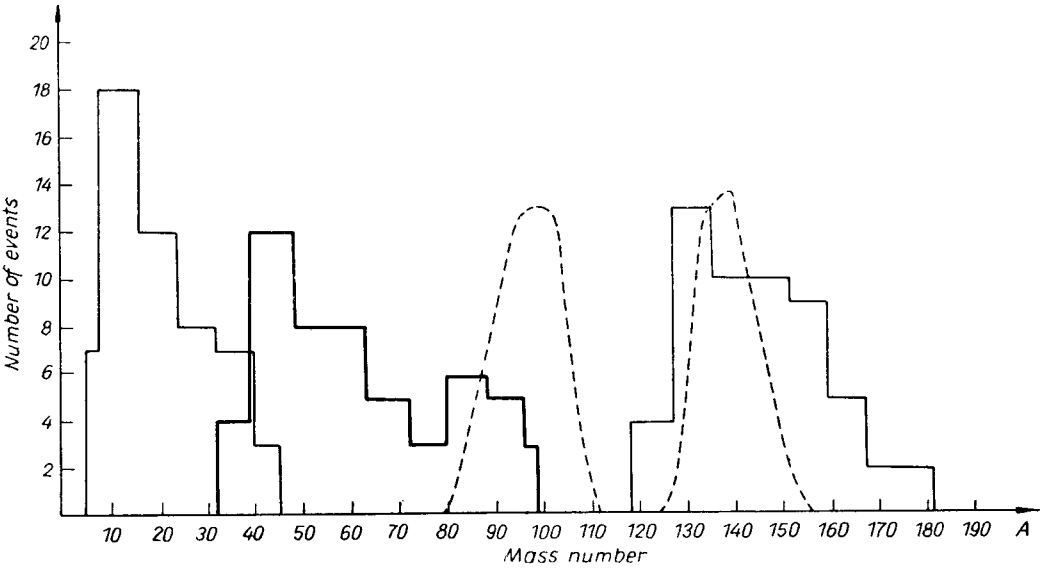

Fig. 9. Mass distribution for ternary fission fragments of $^{239}_{92}$U for type I events. Dotted curves represent the corresponding mass distribution for binary fission as obtained in Ref. [4]

to the same heigt. Mass distributions for binary fission of $^{238}_{92}$U and $^{232}_{90}$Th were taken from Ref. [4].

The total kinetic energy release in ternary fission of $^{238}_{92}$U and $^{232}_{90}$Th induced by 2.9 MeV neutrons is not constant and may depend on the mode of tripartition. In this experiment the accuracy of total kinetic energy can be estimated as 8 per cent. The full width at half maximum for the total kinetic energy spectrum is about 93 MeV for ternary fission of $^{239}_{92}$U and 107 MeV for ternary fission of $^{232}_{90}$Th. The average total kinetic energy release in ternary fission of $^{239}_{92}$U and $^{233}_{90}$Th is 174.5 MeV and 162 MeV respectively.

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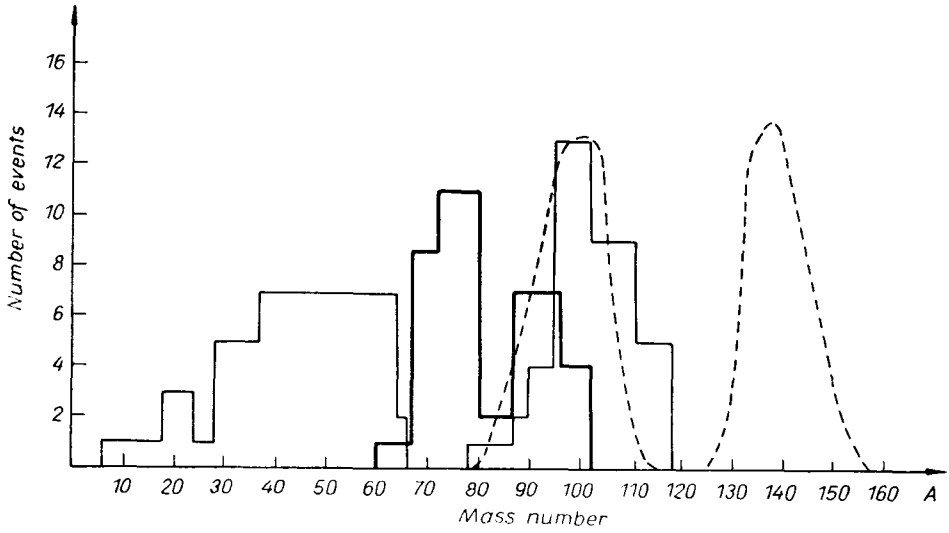

Fig. 10. Mass distribution for ternary fission fragments of $^{239}_{92}$U for type II events. Dotted curves represent the corresponding mass distribution for binary fission as obtained in Ref. [4]

The frequency of occurence of ternary fission relative to binary fission was found to be 8×10^{-4} for $^{238}_{92}$U and 3×10^{-3} for $^{232}_{90}$Th nuclei. Cross sections of ternary fission of $^{238}_{92}$U and $^{232}_{90}$Th for 2.9 MeV neutrons were not reported so far. The cross section of ternary fission of $^{232}_{90}$Th induced by 2.5 MeV neutrons was estimated by Hill and Wheller as 10^{-3}—10^{-4} [2]. The cross section of ternary fission of $^{232}_{90}$Th with the emission of $^{8}_{4}$Be for 2.5 MeV neutrons was found by Titterton [5] as 8×10^{-5}. For an emission of Be cross sections of ternary fission od $^{232}_{90}$Th and $^{238}_{92}$U induced by 2.9 MeV neutrons were found to be 8×10^{-5} and 7×10^{-5}, respectively. These values are in good agreement with the cross section obtained by Titterton.

Discussion

Events of ternary fission of $^{238}_{92}$U and $^{232}_{90}$Th induced by 2.9 MeV neutrons may be divided into two classes: type I events and type II events. They show two maxima in the heavy fragment mass distribution (Figs 2 and 8). Type I events are represented in the peak "*b*". Type II events are represented in the peak "*a*". Mass distributions (heavy, medium and light fragments) for type I events only, are shown in Fig. 9. Type I events are characterized by the formation of a heavy fragment of similar mass ($\bar{A}_H = 146\pm17$ for ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons and $\bar{A}_H = 148\pm10$ for ternary fission of $^{232}_{90}$Th induced by 2.9 MeV neutrons) as that for binary fission ($A_H = 139$). The third fragment of ternary fission of $^{232}_{90}$Th and $^{238}_{92}$U induced by 2.9 MeV neutrons is probably emitted from the light fragment of binary fission. The average total mass number of a medium and a light fragment of ternary fission of $^{232}_{90}$Th and $^{238}_{92}$U induced by 2.9 MeV neutrons is within the limits of error in agreement with the mass number of the light binary fission fragment. This mode

of ternary fission was called asymmetrical ternary fission [1]. Mass distributions for ternary fission fragments of $^{238}_{92}$U induced by 2.9 MeV neutrons (heavy, medium, and light fragments) for type II events only are shown in Fig. 10. For heavy fragments of ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons (Fig. 2, peak "a") the average mass number ($\bar{A}_{HL} = 102 \pm 11$) is in good agreement with the most probable mass number of the light binary fission fragment ($A_L = 98$). The third fragment of tecnary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons is probably emitted from the heavy fragment of binary fission. The average total mass number of a medium and a light fragment is within limits of error in agreement with the mass number of the heavy binary fission fragment.

Energy-mass correlations of ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons (Figs 3, 5, and 7) and mass distributions for ternary fission fragments of $^{238}_{92}$U induced by 2.9 MeV neutrons (Fig. 2, peak "b") and $^{232}_{90}$Th induced by neutrons of the same energy (Fig. 8) are similar to those of $^{235}_{92}$U induced by thermal neutrons [1].

The third fragment of ternary fission of $^{238}_{92}$U induced by 2.9 MeV neutrons is probably emitted from the light or heavy fragment of binary fission. This mode of ternary fission according to the suggested mechanism of tripartition was called asymmetrical ternary fission.

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