

*ENERGY SPECTRUM OF THE FRAGMENTS FROM THE TRIPLE FISSION OF U<sup>235</sup>*

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Data are presented on the energy distribution of fragments from the triple fission of U<sup>235</sup>. It is shown that the ratio of the probability for triple fission to the probability for double fission does not depend on the ratio of fragment masses. We establish the relation (1) between the total kinetic energy of the fragments in triple and double fission and the energy of the long-range  $\alpha$  particle. The mechanism of triple fission is discussed.

INFORMATION on the mechanism of nuclear fission can be obtained from the study of fission events in which a long-range  $\alpha$  particle is emitted. This is because the  $\alpha$  particle is emitted at the very beginning of the fission process and so characterizes the state of the nucleus at the moment of fission. This subject is reviewed in an article by Perfilov, Romanov, and Solov'eva.<sup>1</sup>

Until recently, the energy distribution of the fragments from triple fission had not been adequately studied. The most commonly used method for studying triple fission, that of emulsion stacks, can only give approximate information on the energy distribution of the fragments. Allen and Dewan<sup>2</sup> were the first to use an ionization chamber and grid to study the energy distribution of fragments from triple fission. The U<sup>235</sup> target was placed in a double ionization chamber, one half of which detected fission fragments while the other half registered the  $\alpha$  particles emitted during triple fission. Triple fission events were identified by coincidences between the two chambers. Unfortunately, this method has a fundamental drawback in that the results are distorted by the angular correlation between the fission fragments and the  $\alpha$  particle. It is known that the most probable angle between the direction of emission of the  $\alpha$  particle and the direction of emission of the lightest fission fragment is about 80°. Since the hemisphere associated with a heavy fragment contains fewer long-range  $\alpha$  particles than does the hemisphere associated with a light fragment, coincidences between heavy fragments and  $\alpha$  particles were detected with a higher efficiency than were coincidences between light fragments and an  $\alpha$  particle. For this reason, the area of the peak corresponding to the group of heavy fragments is considerably larger than the area of the peak corresponding to light

fragments, so that the distribution obtained is only a crude approximation to the real one.

We undertook a more detailed investigation of the energy spectrum of fragments from the triple fission of uranium.<sup>3</sup> The conditions of the experiment were such that the results were insensitive to angular correlations. It was found that the height of the peak corresponding to light fragments was greater, not smaller, than the height of the peak corresponding to the heavy fragments, while the half-widths of the peaks were approximately the same. The most probable value for the sum of the kinetic energies of the fragments in triple fission, plus the kinetic energy of the  $\alpha$  particle, turned out to be approximately equal to the most likely value for the total kinetic energy of the fragments in double fission.

In a recently published paper, Mostovoĭ et al.<sup>4</sup> describe an experiment using the first method, but in which a correction was applied for the angular correlation between the fission fragments and the  $\alpha$  particle. This correction is based on an extrapolation of data on the distribution of light fragments and also involves the angular distribution of the  $\alpha$  particles, this latter distribution only being known with poor statistical accuracy. There is satisfactory agreement between the results quoted in references 3 and 4.

The work being reported upon here was carried out in order to get more detailed and reliable data on the energy spectrum of fragments from the triple fission of U<sup>235</sup>. In order to do this, we measured the energies of pairs of fragments.

**EXPERIMENTAL SETUP**

In making measurements of the energy distribution of fragments from triple fission, the effect of angular correlation between the  $\alpha$  particle and

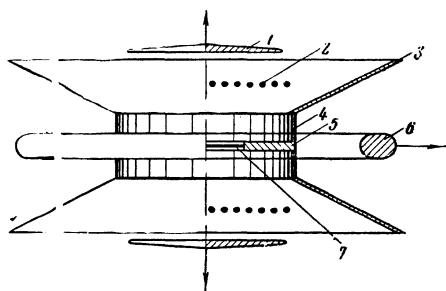


FIG. 1. Positions of the electrodes in the triple ionization chamber: 1 - collector for the fission chamber; 2 - grid for the fission chamber; 3 - cone; 4 - grid; 5 - common electrode for the fission chambers; 6 - collector for the  $\alpha$  chamber; 7 - target.

the fragments can be excluded by counting  $\alpha$  particles on both sides of the target containing fissionable material. We have built a triple ionization chamber, together with its associated electronic circuitry.

The ionization chamber is shown schematically in Fig. 1. The chamber has cylindrical symmetry. The volume of the  $\alpha$  chamber (the chamber for detecting long-range  $\alpha$  particles) is defined by the cones and a metallic grid, the two together being one electrode of the  $\alpha$  chamber. The other electrode of the  $\alpha$  chamber is a metal ring. The electrode common to the two fission chambers and the first electrode of the  $\alpha$  chamber were at ground potential. The supports and insulators were made of fluoroplastic.<sup>5</sup> The chamber was filled with argon at a pressure of two atmospheres. This pressure was high enough that  $\alpha$  particles from naturally radioactive uranium could not reach the  $\alpha$  chamber, which counted only long-range  $\alpha$  particles with energies of 10 to 24 Mev.

The target of fissionable material was fastened to the common electrode of the fragment chambers. It was supported by a polyvinylchloride-acetate film<sup>6</sup>  $5\mu\text{g}/\text{cm}^2$  thick. Both sides were covered with  $\sim 6\mu\text{g}/\text{cm}^2$  of gold by vacuum deposition. The  $U^{235}$  was deposited on one side of its support by a sputtering technique,<sup>7</sup> the thickness of the layer being  $\sim 10\mu\text{g}/\text{cm}^2$ .

A block diagram of the electronics is shown in Fig. 2. After passing through amplifying and pulse-shaping circuits, pulses from the fission chambers were fed onto the vertical (channel 1) and horizontal (channel 2) deflecting plates of an oscilloscope tube. The beam in the tube could be cut off so that no pulses were displayed unless there was a pulse from the  $\alpha$  particle - fission fragment coincidence circuit. The position of the deflected beam was recorded photographically. When there were no pulses, the beam was focused

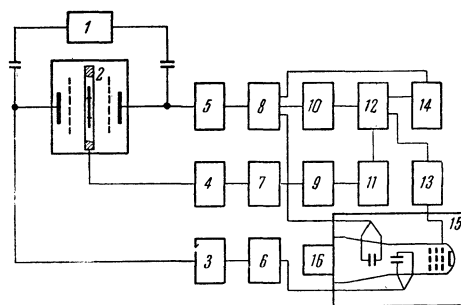


FIG. 2. Block diagram of the electronic circuitry: 1 - generator for calibrating pulses; 2 - chamber; 3, 4, 5 - preamplifiers; 6, 7, 8 - amplifiers; 9, 10 - discriminators; 11 - delay; 12 - coincidence circuit; 13 - brightness control; 14 - 63-channel pulse-height analyzer; 15 - oscilloscope; 16 - camera.

on a point in the lower left hand corner of the field of view, this point being the origin of coordinates. When pulses were produced by the fission fragments and by the coincidence circuit, a dot would appear in the field of view, the distance of the dot from the vertical and horizontal axes being proportional to the amplitude of the first and second pulses. When observing fragments from double fission, the  $\alpha$  channel was disconnected.

The photography was in the following sequence. The output of a calibrating generator was fed into the preamplifiers for the fission channels, the purpose of the calibrating generator being to illuminate three dots on the scope face, the dots defining the two coordinate axes and the origin. The stability of the entire apparatus was monitored by these three dots. The diameter of the dots was less than 1% of the full scale deflection the beam could undergo, so that one frame on the film could record about 80 - 100 dots (pairs of pulses). After these were recorded, the next frame would advance into position and the process would be repeated. Data taken this way were conveniently analyzed and were not subject to errors due to motion of the film while data was being recorded, or to the motion of the film in the projector while data was being analyzed.

The nonlinearity of the fission channels - from the input of the preamplifiers to the film - was less than 2%. After 30 min of warm-up time, the apparatus was stable to better than 2% over many hours.

The fraction of accidental coincidences was determined by the background pulses arising from neutron bombardment of the contaminants in the gas and of the  $\alpha$ -chamber walls. To minimize this effect, the neutron beam was well collimated and was directed so as to miss the  $\alpha$ -chamber walls. The effects of neutron scattering were

minimized by admitting the beam to the fragment chamber through a thin aluminum window, and by placing a second window at the exit of the neutron beam from the fragment chamber. Under these conditions, the accidental coincidences amounted to less than 3% of the true coincidences and were neglected in the analysis.

## RESULTS

The work being described was carried out with the research reactor of the U.S.S.R. Academy of Sciences. The  $U^{235}$  target was irradiated by neutrons whose spectrum was that of the pile neutrons. About 8000 cases of triple fission and 6000 cases of double fission were observed.

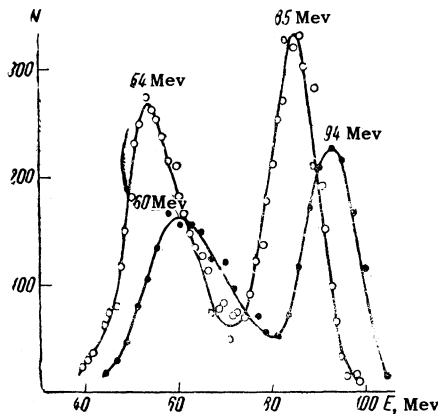


FIG. 3. Energy distribution of fragments from  $\circ$  - triple and  $\bullet$  - double fission of  $U^{235}$ . No correction for ionization effect.

Figure 3 shows the spectrum of fragments from triple and double fission, as obtained from observations on the chamber on the  $U^{235}$  side of the target. These data are corrected for the ionization produced by long-range  $\alpha$  particles in passing through the fission chambers. It is clear from the diagram that the two distributions are displaced with respect to each other. The peak corresponding to light fragments is displaced ( $9.0 \pm 0.5$ ) Mev in the direction of lower energy, while the displacement of the peak corresponding to heavy fragments is ( $6.0 \pm 0.5$ ) Mev.

The half-widths of the light and heavy fragment peaks in triple fission are less than the corresponding half-widths for double fission. The spectra obtained from the second fission chamber are similar to the spectra shown in Fig. 3. A shift of  $\sim 2$  Mev was observed and ascribed to energy loss in the target backing.

Figure 4 shows the yield of fragments from triple and double fission as a function of the total kinetic energy of the fragments. These curves are

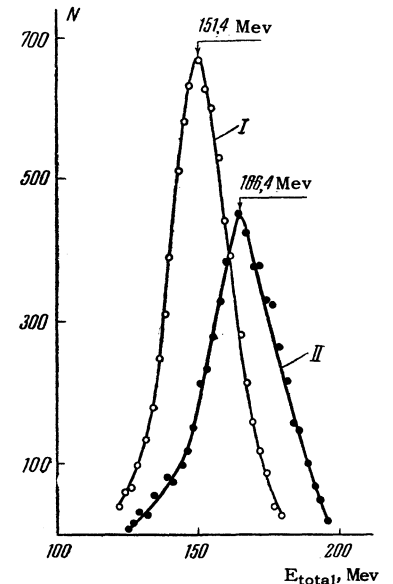


FIG. 4. Number of events as a function of total kinetic energy for  $\circ$  - triple and  $\bullet$  - double fission (with correction for ionization defect).

corrected for the ionization defect, which amounts to 12.4 Mev.<sup>8</sup> The difference between the most probable energies in double and triple fission is ( $15.0 \pm 0.5$ ) Mev. The half-width of the peak corresponding to triple fission is 3 Mev less than the half-width for the peak corresponding to double fission. The distributions are Gaussian to a good approximation.

The data were reduced to yield the dependence of the yield in both double and triple fission on the mass ratio of the fragments. Since the correction for the momentum of the  $\alpha$  particle was small, it was assumed that the relation  $M_1E_1 = M_2E_2$  held for triple as well as for double fission. The ioni-

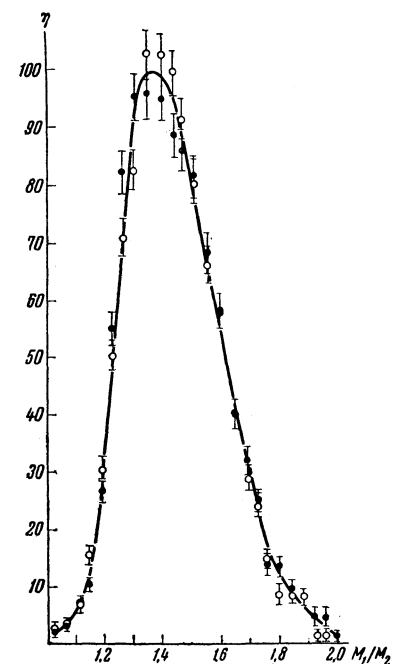


FIG. 5. The yield  $\eta$  of double ( $\bullet$ ) and triple ( $\circ$ ) fission as a function of the ratio of fragment masses. The yield is given in arbitrary units.

zation defect was assumed to be a linear function of the mass of the fragment:  $\Delta E(M) = (4.0 \pm 0.019M) \text{ Mev}$ .<sup>9</sup> Upon normalizing the distributions to equal area it was found that the two distributions agreed within the statistical errors (Fig. 5). Both peaks occur at a mass ratio  $M_1/M_2 = 1.4$ . The half-widths of the distributions are the same and amount to  $\sim 16$  mass units.

Finally, Fig. 6 shows the most likely total kinetic energy and the dispersion of the total kinetic energy of the fragments as a function of mass ratio. According to Protopopov, Baranov et al.<sup>10</sup>, the maxima at mass ratio 1.3 can be explained in terms of shell structure.

## DISCUSSION OF RESULTS

We have found that the half-widths of the energy distributions for fragments from double and triple fission differ from each other (Fig. 3). It might be suggested that the narrower peak observed for triple fission might be connected with a mass distribution which is more asymmetric for triple fission than it is for double fission. However, this does not agree with the observed mass distributions for triple and double fission, since these mass distributions are identical (to within the mass of the  $\alpha$  particle) (Fig. 5). In other words, the probability of triple fission relative to double fission does not depend on the mass ratio. This disagrees with Hill's conclusion that triple fission should favor the formation of fragments with approximately equal masses.<sup>11</sup>

Our data show that the relation

$$E_d = E_{tr} + E_\alpha \quad (1)$$

holds,  $E_d$  and  $E_{tr}$  being the total kinetic energies of the fission fragments in double and triple fission respectively, while  $E_\alpha$  is the energy of the  $\alpha$  particle. For the most likely energy in double and triple fission we have, in particular,  $E_d = 166.4 \text{ Mev}$ , while  $E_{tr} + E_\alpha = 151.4 + 14.8 = 166.2 \text{ Mev}$ . All the fundamental data obtained in this and in previous work can be explained on the basis of equation (1).

First of all, the relation (1) implies that

$$(\Delta E_d)^2 = (\Delta E_{tr})^2 + (\Delta E_\alpha)^2,$$

where  $\Delta E_d$ ,  $\Delta E_{tr}$  and  $\Delta E_\alpha$  are the half-widths of the corresponding distributions. From this it is clear why the half-width of the total kinetic energy distribution for triple fission is less than the corresponding half-width for double fission. The same relation leads to information about the energy spectrum of the long-range  $\alpha$  particles. Since

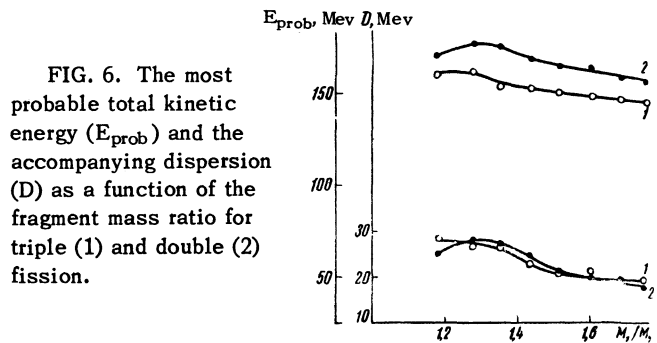


FIG. 6. The most probable total kinetic energy ( $E_{prob}$ ) and the accompanying dispersion ( $D$ ) as a function of the fragment mass ratio for triple (1) and double (2) fission.

$\Delta E_d = 28 \text{ Mev}$ , and  $\Delta E_{tr} = 25 \text{ Mev}$ , it follows that  $\Delta E_\alpha = 13 \text{ Mev}$ . The maximum of this distribution should occur at 15 Mev. These numbers are in good agreement with the experimental data on the energy distribution of the long-range  $\alpha$  particles:  $\Delta E_\alpha = 11 \text{ Mev}$  and  $E_\alpha$  (most likely) = 14.8 Mev.<sup>12</sup>

According to Fong's theory,<sup>13</sup> the ratio of the probabilities for double and triple fission is determined by the difference between the total excitation energies of the fragments. Calculations show that when (1) is satisfied, then the difference between the total excitation energies of the fission fragments in double and triple fission depends but little on the fragment mass ratio and is about 4 Mev. Hence the probability for triple fission relative to double fission should not depend on the mass ratio. This explains the fact that the mass distributions in triple and double fission are the same (to within the mass of the  $\alpha$  particle).

Decreasing excitation energy leads to a decrease in the probability for triple fission relative to that for double fission. Furthermore, a decrease in excitation energy should lead to the emission of fewer neutrons and  $\gamma$  rays in triple fission. Experimentally, it has been found<sup>4</sup> that the average number of prompt neutrons per triple fission is  $\bar{\nu}_{tr} = 1.77 \pm 0.09$  for  $E_\alpha \geq 9 \text{ Mev}$ , which is significantly less than the corresponding number for double fission. In reference 14, it was found that  $\bar{\nu}_{tr} = 1.79 \pm 0.13$  for  $E_\alpha \geq 22 \text{ Mev}$ . In the light of our assumptions, it is clear why the mean number of neutrons per triple fission does not depend on the energy of the  $\alpha$  particles: the point is that in the act of fission there is a redistribution of the kinetic energy among the fragments and the  $\alpha$  particle, but the excitation energy remains the same.

The equality (1) shows that the Coulomb energy of the system just before fission is the same in the two cases, i.e., there is no difference between the nuclear configurations just before double and triple fission and the  $\alpha$  particle does not develop from a special "necking" process.

The mechanism for triple fission might be pictured as follows: just before fission, the potential barrier near the neck of the deformed nucleus becomes lower. During fission, the particles at the surface of the nucleus are strongly accelerated, which leads to a further lowering of the barrier because of "inertial forces" and so enhances the probability for emission of an  $\alpha$  particle. Right up to the instant of fission, the nucleus "does not know" whether to split into two or three parts, which makes it plausible that the various quantities plotted in Figs. 3–6 are the same for double and triple fission. This picture suggests that the probability for triple fission does not change markedly from nucleus to nucleus, and this is observed experimentally.<sup>15</sup> The decrease in the probability for triple fission observed as the energy of the bombarding neutrons is increased presumably is due to competition from other processes (for example, neutron emission at the moment of fission).

The mechanism for triple fission which has just been described offers a qualitative explanation both for the observed anisotropy in the angular distributions of the long-range  $\alpha$  particles and fission fragments, and also for the decrease in anisotropy for higher energy  $\alpha$  particles.<sup>16–18</sup>

In conclusion it should be stressed that the study of triple fission leads to a number of detailed and interesting insights into the fission process in general.

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<sup>1</sup>Perfilov, Romanov, and Solov'eva, *Usp. Fiz. Nauk*, in press.

<sup>2</sup>K. W. Allen and J. T. Dewan, *Phys. Rev.* **80**, 181 (1950).

<sup>3</sup>Dmitriev, Drapchinskiĭ, Petrzhak, and Romanov, *Dokl. Akad. Nauk SSSR* **127**, 531 (1959), *Soviet Phys.-Doklady* **4**, 823 (1960).

<sup>4</sup>Mostovoĭ, Mostovaya, Sovinskiĭ, and Saltykov, *Атомная энергия (Atomic Energy)* **7**, 372 (1959).

<sup>5</sup>Dmitriev, Drapchinskii, and Romanov, *Приборы и техника эксперимента (Instruments and Exptl. Techniques)*, in press.

<sup>6</sup>B. D. Pate and L. Jaffe, *Can. J. Chem.* **33**, 15 (1955).

<sup>7</sup>Gorodyskiĭ, Romanov, Sorokina, and Yakunin, *op. cit. ref. 5*, No. 5, 128 (1959).

<sup>8</sup>R. B. Leachman, *Phys. Rev.* **87**, 444 (1952).

<sup>9</sup>J. Fraser and J. Milton, *Phys. Rev.* **93**, 818 (1954).

<sup>10</sup>Protopopov, Baranov, Selitskiĭ, and Éĭsmont, *ЖЭТФ* **36**, 1932 (1959), *Soviet Phys. JETP* **9**, 1374 (1959).

<sup>11</sup>D. L. Hill, *Second UN International Conference on the Peaceful Uses of Atomic Energy*, **15**, 244 (1958) [Paper P/660].

<sup>12</sup>C. Fulmer and B. Cohen, *Phys. Rev.* **108**, 370 (1957).

<sup>13</sup>P. Fong, *Phys. Rev.* **102**, 434 (1956).

<sup>14</sup>Apalin, Dobrynin, Zakharova, Kutikov, and Mikaĕlyan, *op. cit. ref. 4*, **7**, 375 (1959).

<sup>15</sup>Dmitriev, Drapchinskiĭ, Petrzhak, and Romanov, *ЖЭТФ* **38**, 998 (1960), *Soviet Phys. JETP* **11**, 718 (1960).

<sup>16</sup>Tsien, Ho, Chastel, and Vigneron, *J. Phys. Radium* **8**, 165 (1947).

<sup>17</sup>E. Titterton, *Nature* **168**, 590 (1951).

<sup>18</sup>N. A. Perfilov and Z. I. Solov'eva, *ЖЭТФ* **37**, 1157 (1959), *Soviet Phys. JETP* **10**, 824 (1960).

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