Energy Distribution of the Fragments Resulting from the Fission of U^{235} and Th^{232} by Slow and by Fast Neutrons*

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The distribution of energies of the fragments from U^{235} fission produced by slow and by fast neutrons were compared. The energy was determined by using a 10-channel amplitude discriminator to analyze pulses from a Frisch-grid ionization chamber. No difference was found outside the experimental error. The energy distribution of the fragments from thorium fission was also determined. The high energy tails of the distributions were especially investigated for the purpose of detecting the occurrence of triple fission. This indicated a negative result. A possible correlation between the most probable mode of disintegration of the nucleus and its atomic number suggests itself.

1. INTRODUCTION

A CONSIDERABLE number of experiments have been performed in which the primary objectives were to measure the kinetic energy liberated in the fission of uranium and to determine how this energy is distributed between the fission fragments.[1–11] Of all these studies, the only ones which are in good agreement on the details of the energy distribution of the fission fragments are those of Jentschke and Deutsch.

In virtually all of the investigations made to date, where the energies of the individual fission fragments were determined, the experimental procedure involved the photographing and subsequent measuring of the ionization pulses produced by the fission fragments, a procedure which necessarily limits the statistical accuracy of the results.

The present investigation was undertaken for three reasons:

TABLE I. Comparison of data on fission products from U^{235} and Th^{232}.

	Position of high energy peak (Mev)	Position of low energy peak (Mev)	Width at half-maximum for high energy peak (Mev)	Width at half-maximum for low energy peak (Mev)	Ratio of minimum to high energy peak (%)	Ratio of peak energies	Ratio of peak heights	Foil thickness (mg/cm²)
$_{92}U^{235}$—Slow neutrons								
Jentschke	95.5	65	13	20	5	1.47	1.49	0.04
Deutsch	94	60	11	18	12.5	1.56	1.57	0.001
Fowler and Rosen	92.5	61.2	15	24.5	14.4	1.50	1.46	0.029
Fowler and Rosen	93	61.8	17.8	25.5	21	1.50	1.43	0.105
$_{92}U^{235}$—Fast neutrons								
Fowler and Rosen	92.5	62	14.7	25	16.1	1.49	1.44	0.029
$_{90}Th^{232}$								
Jentschke	91	60	14.6	23.3	20	1.51	1.5	0.04
Fowler and Rosen	92.6	58.3	19.1	23	24	1.59	1.12	0.146

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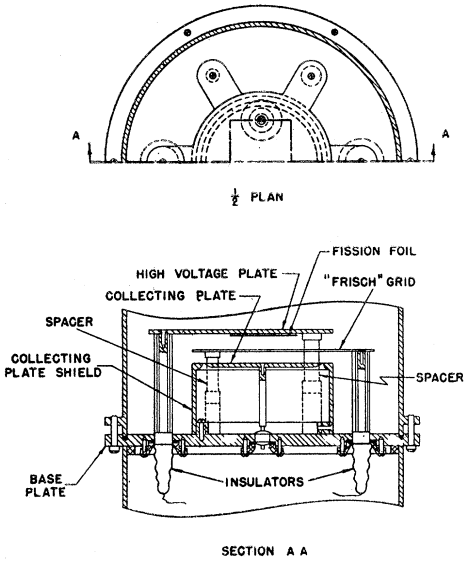

FIG. 1. Schematic diagram of the ionization chamber.

(1) To obtain the energy-distribution curve for the fission fragments from U^{235} by the use of an electronic method for measuring and counting the ionization pulses produced by these fragments in an ionization chamber;

(2) To determine whether the energy-distribution curve is a function of the incident-neutron energy;

(3) To investigate the high energy portion of the curve for any indication of additional peaks which one might expect if some nuclei divided into more than two fragments.

Item (2) has been investigated to a certain extent by D. Frisch[12] for isotope 92^{237}. He found that the distribution of the fragments in the high energy peak was the same to the accuracy of his measurements when the fission was produced by neutrons of three different energies: 500, 720, and 900 kev.

2. EXPERIMENTAL METHOD

The method used in the present experiments was fundamentally the same as that used in preceding experiments; namely, the comparison of the ionization produced by the individual fission fragments with the ionization produced by α-particles of known energy.

The ionization chamber, Fig. 1, was of the electron-collection type. The screen, which shields the collecting electrode from the positive ions, was made of No. 36 parallel copper wires spaced 1.5 mm apart. The high voltage electrode, on which was mounted the fissionable foil, was kept at 2150 volts while the screen was kept at 1050 volts. This made the field between the screen and collecting electrode slightly higher than the field outside the screen. However, this was desirable in order to insure that the screen should capture a minimum number of electrons.

In order to obtain the energy spectrum of the fission fragments, the chamber was filled with argon to a pressure of 232-cm Hg. This pressure was more than sufficient to stop the highest energy fission fragments before they reached the grid. The gas was continuously purified by circulating it over calcium metal at 300°C. Also, for the sake of purity, the only organic material inside the counter consisted of several rubber washers which exposed very little surface to the gas in the chamber.

The saturation voltage for the ionization chamber was established by determining the position of the energy peaks of the fission-fragment energy spectrum as a function of voltage. When a voltage was reached above which the position of the peak no longer shifted, it was assumed that the chamber was saturated. The counter was operated at approximately 500 volts above the saturation voltage.

The recording equipment consisted of a 10-channel discriminator,[13] each channel having such a width as to accept pulses over a range of about 0.8 Mev for the amplification used. It was possible to shift the bias of all the channels by the same amount so that the entire energy spectrum could be obtained, 9 points at a time. The channel widths had a tendency to drift by ± 5 percent over periods of 10 to 12 hours, but

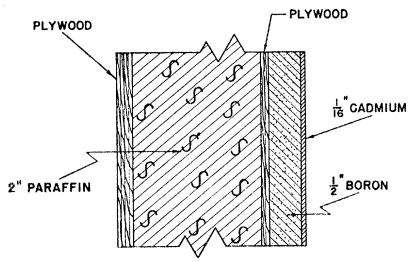

FIG. 2. Wall cross section of paraffin-boron-cadmium "ice box."

[12] D. H. Frisch, Phys. Rev. **71**, 478 (1947).

[13] This instrument, developed by the Los Alamos Scientific Laboratory Electronics Group, will be reported in a future paper by M. Sands and E. Dexter.

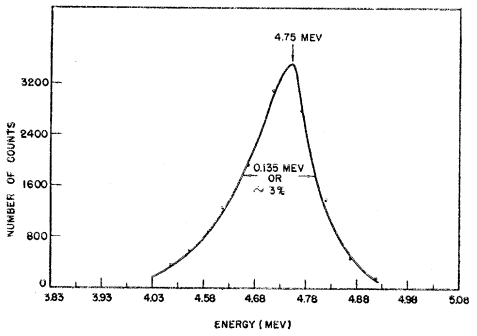

FIG. 3. Energy distribution of uranium^{234} alpha-particles.

much of this error was eliminated by calibrating the channel widths every 30 minutes. A check could always be had on the effectiveness of this procedure as a result of the fact that when the bias on the chamber was shifted, channels 1, 2, and 3 in the new position overlapped channels 7, 8, and 9 of the preceding setting. When everything operated properly the overlapping channels gave values within ± 3 percent of each other. The 10-channel discrimator was fed by a "model 100"[14] amplifier, which in turn was fed by a "model 100" preamplifier adjoining the ionization chamber. The so-called "model 100"[14] amplifier was stabilized by inverse feedback and had a rise time of 0.5μ sec. Instead of using an RC clipping circuit at the input of the amplifier, the incoming pulse was reduced to $\frac{1}{5}$ its size after 9μ sec., step fashion, by superimposing on this signal its inverse reflection. This was accomplished by using a shorted delay line. The 9μ-sec. clipping time appeared to be about three times as great as the electron collection time. The amplifier and 10-channel discriminator was shown to be linear, by use of a precision pulser, to within ± 1 percent.

The neutron source used for these experiments was the Los Alamos cyclotron, using the $Be^9(d,n)B^{10}$ reaction. For the "slow"-neutron experiments, the counter was shielded by 9 inches of paraffin on two sides and by 23 inches of paraffin on the side facing the target (the fourth side faced the cyclotron water tanks). There was also 4 inches of paraffin above the counter and 4 inches below it. For irradiation by "fast" neutrons, the counter was surrounded by a layer of Cd, then by 4 inches of boron and the whole assembly placed inside a parafin, boron, Cd box, a cross section of one of the walls of which is shown in Fig. 2. In order to arrive at some estimate of the energy distribution of the so-called "fast" neutron flux, a U^{238} foil was substituted for the U^{235} foil and the number of fissions for an equivalent beam intensity was determined. From the known cross sections of U^{235} and U^{238} and from the known amounts of active material on the foils, one can arrive at a rough approximation of the energy distribution of the incident neutrons. It turns out that approximately 10 percent of the "fast" flux is comprised of neutrons having energies in excess of 1 Mev while very few of the remainder have energies of less than 1000 ev.

The determination of the energy of the fission fragments in terms of the ionization produced was made on the assumption that α-particles expend the same energy in producing an ion pair as do the fission fragments. In order to determine the ionization produced by U^{234} alpha-particles, it was necessary to increase the pressure in the chamber, by the addition of argon, to 290-cm Hg so as to stop all the alphas before they reached the grid (the fission-fragment energy spectrum was checked at this pressure with no resulting change in the position of the peaks). The ratio of the pulse sizes due to the fission fragments, at various points of the energy-spectrum curve, to the pulse size due to the U^{234} alphas was established by calibrating the amplifier and 10-channel discriminator with a precision pulser.

The width at half-maximum of the α-particle distribution, Fig. 3, serves as a measure of the resolution of the ionization chamber. The noise level, due to the ionization noise and amplifier noise, was equivalent to a particle energy of

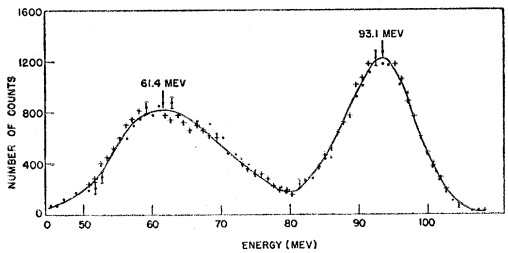

FIG. 4. Energy spectrum of uranium^{235} fission fragments for "slow" neutrons.

[14] Los Alamos Scientific Laboratory designation.

0.4 Mev (the best previous work was done by Deutsch who had a noise level corresponding to a particle energy of 1.5 Mev).

Two foils of 94 percent U^{235} were investigated. These were mounted on 10-mil platinum and contained 0.332 mg and 0.19 mg of metal uniformly distributed over 3.14 cm² and 7.07 cm², respectively. The foils were made by Robert M. Potter and James S. Gilmore of the Los Alamos Scientific Laboratory.

The reason for investigating two foils of different thicknesses was to attempt to obtain data which would aid in correcting for the finite thickness of the foil. Jentschke calculated that for a foil thickness of 0.04 mg/cm², one Mev should be added to the energies of the light and heavy fragments. Since this thickness of foil is slightly greater than the thickness of our thin foil, it would seem that such a correction would be in order for our data, except for the fact that

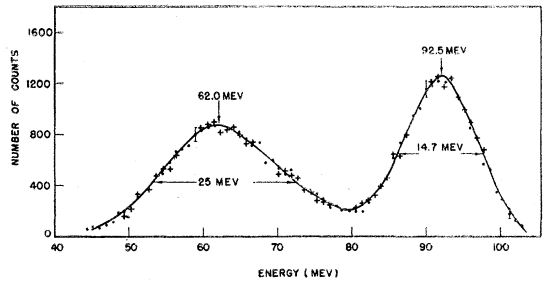

FIG. 5. Energy spectrum of uranium^{235} fission fragments for "fast" neutrons.

in our case almost half of this error is compensated by the energy loss of the alpha-particles used for calibration. This would leave a correction of slightly more than 0.5 Mev to be added to the energy of the light and heavy fragments and this is well within the experimental error. It is therefore not surprising that no difference can be detected between the curves for the foils of thicknesses 0.026 mg/cm² and 0.106 mg/cm² as far as the position of the peaks is concerned.

3. RESULTS

Characteristic sets of determinations of the fission-fragment distribution as a function of energy for "slow" and for "fast" neutrons are plotted in Figs. 4 and 5. As a check on these curves, it was determined that the area under each of the two peaks in each curve was the same to within 4 percent. Table I compares the results given here with the best values previously obtained.

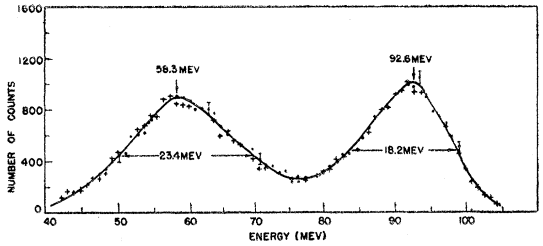

FIG. 6. Energy spectrum of thorium^{232} fission fragments.

There seem to be no significant differences between the curves for "fast" and for "slow" neutrons, although the minimum in the case of the "fast" neutrons appears to be about 1.5 percent higher than the minimum in the case of the "slow" neutrons.

No extra peaks are discernable in the high energy region for fast or for slow neutrons. In order to check this conclusion for high energy neutrons (up to 26 Mev), a Li target, made by Stanley Hall, was substituted for the Be target at one stage of the experiment but the curve still showed no signs of extra peaks. The data permit one to conclude that if certain atoms break up into more than two fragments of comparable masses, this phenomenon occurs less frequently than once in 1000 fissions.

The energy distribution of the fission fragments for Th^{232} was also determined. The thorium foil was also prepared by Potter and Gilmore. This curve is given in Fig. 6. This experiment had previously been performed by Jentschke

TABLE II. Data on high and low energy fission products.

Isotope	Investigator	Ratio of energy of high energy peak to low energy peak	Most probable ratio of energy of fragments
$_{90}Th^{232}$	Jentschke[4]	1.51	
	Fowler and Rosen	1.59	
$_{92}U^{235}$	Jentschke[4]	1.47	
	Deutsch[1]	1.57	1.49
	Fowler and Rosen	1.51	
$_{92}U^{238}$	Kanner and Barschall[3]	1.52	
$_{94}Pu^{239}$	Deutsch[1]	1.43	1.32

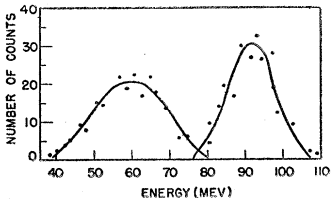

FIG. 7. Jentschke's curve for thorium^{232}.

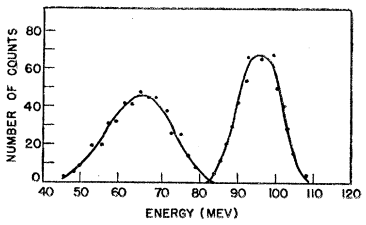

FIG. 8. Jentschke's curve for uranium^{235}.

and his results are given in Fig. 7. Jentschke arrived at a curve very similar to his curve for U^{235} shown in Fig. 8. Table I also shows a comparison between our results and Jentschke's for thorium. It should be pointed out that our foil was relatively thick (0.14 mg/cm^2) while Jentschke's foil contained only 0.04 mg/cm^2. This probably accounts for the discrepancy as regards the minimum between the two peaks, in view of the difference in minima obtained for the two foils of U^{235} (Table I), which foils differed in thickness by a factor of about 3. Considerable difference exists between the spectra for thorium, aside from the difference in the minima. It should be pointed out, however, that Jentschke's curves were determined with very poor statistics; the statistical error of his high energy peak being approximately 18 percent. Further experiments will be resorted to in order that this discrepancy may be resolved.

It is of considerable interest to compare the energy distribution of fragments for all the different isotopes measured. This involves comparing the results of several different experimenters. Perhaps the most reliable quantity determined is the ratio of energy of the high energy peaks to that of the low energy peaks, since this quantity depends on the linearity of the detecting apparatus and not on an absolute-energy scale. Because of conservation of momentum, this ratio gives also the ratio of the masses of the fragments for the most probable mode of fission. This is not quite true because of the momentum of the prompt neutrons emitted during the fission process, however, only a slight error is introduced on this account particularly if the neutrons are emitted with about equal probability by both fragments. Table II gives the ratio of the peak energies for four isotopes. There seems to be a considerable discrepancy between the value of the ratio as determined by different investigations. In the case of Deutsch's experiment in which both fragments of a pair are measured, by use of a double counter, the most probable ratio of the energies of a pair seems to be somewhat lower than the most probable ratio of peak energies. The former value of the ratio seems to be in better agreement with the results of Jentschke and of this report in the case of U^{235}. All the separate experiments, however, show a tendency for the fission to become more symmetrical as the atomic number of the original nucleus is increased. Holding the atomic number constant and increasing the atomic weight does not seem to affect the asymmetry as markedly. A consistent set of data with good statistics on all the isotopes, however, is needed in order to establish this apparent variation of asymmetry of fission with charge of the nucleus.

We wish to acknowledge the contribution of Stanley H. Hall who ran the cyclotron during this experiment.