KINETIC ENERGY OF FRAGMENTS PRODUCED IN SYMMETRIC FISSION OF U^{235}

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The mean kinetic energy of fragments produced in symmetric fission of U^{235} induced by 7-, 14.5-, and 20-MeV neutrons is measured. It is shown that in the investigated neutron energy range the energy of fission fragments does not change, within the experimental errors. The results of the measurements are discussed from the standpoint of the hypothesis of existence of two types of fission.

INTRODUCTION

SEVERAL recently investigations [1-4] added to our knowledge of the mass spectrum of fission fragments in light of the hypothesis of Turkevich and Niday [5] that there are two independent types of fission, symmetrical and asymmetrical. The first convincing evidence in favor of the existence of two independent types of fission was obtained by Fairhall [1] in a study of the energy dependence of the mass distribution of the fragments of proton and deuteron induced fission of Ra^{226}. Fairhall has also shown, on the basis of data on the fragment mass yields for different fissioning nuclei (from Po to Pu) that the probabilities of the symmetrical and asymmetrical types of fission depend differently on the excitation energy and on the mass of the fissioning nucleus. Ford [2] and Levy et al [3] have established from an analysis of the energy dependence of the yields of several "mass chains" produced by fission of different nuclei that the distribution of the fragment mass can be represented in the form of a linear combination of the independent distributions corresponding to the asymmetrical and symmetrical types of fission. It was also noted in [3] that the charge distributions are noticeably different in these types of fission.

Selitskiĭ and Éĭsmont [4] have attempted to compare symmetrical and asymmetrical fission on the basis of several other characteristics. Using the results of measurements of the distribution of the kinetic energy E_k of a pair of fragments for γ-ray fission of Th^{232} and U^{238}, carried out by Bogachov et al [6,7], Selitskiĭ and Éĭsmont have shown that symmetrical fission corresponds to a value approximately 15 MeV lower than asymmetrical fission. In addition, they reached the conclusion that symmetrical fission, unlike asymmetrical fission, is a fast process. The main motives for such a conclusion were the results of experiments showing that the kinetic energy of the fragments in the fission of U^{235} [8,9] and U^{238} [10,11] by 14-MeV neutrons near the mass ratio $M_H/M_L \sim 1$ is approximately 20 MeV larger than in the fission of U^{235} by thermal neutrons [12]. In other words, Selitskiĭ and Éĭsmont assume that the symmetrical fission process is so fast that the kinetic energy E_k of the neutron causing the fission is practically entirely converted into energy of relative motion of the fragments.

The last statement seems to us insufficiently well founded, since the identification of the yield of fragments with a mass ratio near unity in the fission of thermal neutrons with the yield of the symmetrical type fission at the corresponding excitation energy is not obvious. The point is that the threshold of symmetrical fission is several MeV higher than that of asymmetrical fission, and consequently in fission by thermal neutrons the yield of the symmetrical fission should be much smaller than the observed yield of fragments with approximately equal masses. In addition, it is very difficult to visualize a "fast" fission mechanism proceeding via a compound nucleus, in which the excitation energy is concentrated principally in the nucleon degrees of freedom at the initial stage, and then goes over completely into degrees of freedom connected with the relative motion of the fragments.

The reasons why E_k for $M_H/M_L \sim 1$ increases on going from fission by thermal neutrons to fission by 14-MeV neutrons is analyzed in [9] from a different point of view, but also on the basis of the hypothesis that there are two methods of fission. In the entire interval of the energies E_n, symmetrical fission is assumed to be of the subbarrier type, and the rapid increase in its probability with increasing E_n, in analogy with the mechanism of α-particle emission, is connected with the increase in the kinetic energy of the fragments.

In connection with these considerations, it appears to be of interest to check directly the dependence of the energy E_k^S (for the symmetrical type of fission) on the excitation energy of the fissioning nucleus. We have measured the average kinetic energy of the fragments for symmetrical fission of U^{235} by neutrons with energies 7, 14.5, and 20 MeV.

MEASUREMENT METHOD

We used a double ionization chamber with grids. A layer of fissioning substance (enriched to 90% U^{235}) of thickness 15 mg/cm^2 was deposited on a polyvinyl-chloride-acetate polymer film 5 mg/cm^2 thick. The mass distribution was determined by measuring the ratio of the amplitudes of pulses produced by the two fragments in a single fission act. To measure the ratio of the amplitudes, the pulses were fed to the input of a special electronic unit, the output of which were pulses with amplitude proportional to the ratio of the smaller pulse to the larger one. The investigated fragment mass ratio interval $M_L/M_H = 1-0.9$ was separated with a single-channel analyzer, controlled by a gate that passed the pulses from one-half of the chamber to the input of a 100-channel analyzer. The gain in the channels was set equal and maintained accurate to 1% during the measurement process. The calibration of the pulse amplitude distributions in symmetrical fission was carried out against the average kinetic energy for all the mass ratios in fission by thermal neutrons.

The sources of neutrons with energies 7, 14.5, and 20 MeV were the reactions $B^9(d, n)B^{10}$ and $T(d, n)He^4$, realized with the aid of an electrostatic generator. In spite of the fact that the spectrum of the produced neutrons extended in the reaction $Be^9(d, n)B^{10}$ from several hundred keV to 8 MeV, the average energy of the neutrons causing the symmetrical fission of U^{235} was close to the upper limit of the spectrum.

MEASUREMENT RESULTS

Figure 1 shows the measured distributions of the fragment masses, the abscissas being the ratios M_L/M_H of the masses of the light to the heavy fragments. The mass distributions were normalized to equal yield at the most probable mass ratio. It must be borne in mind that when working with a beryllium target the asymmetrical fission is produced by all the emitted neutrons, and the symmetrical fission is produced essentially by neutrons with energy close to 7 MeV. This circumstance leads to a decrease in the relative yield for the symmetrical type of fission. The increase of the yield of fragments with mass ratio close to unity at E_n equal to 14.5 and 20 MeV is connected with the increase in the yield of the symmetrical type of fission, the distribution of which has a maximum when $M_L/M_H = 1$.

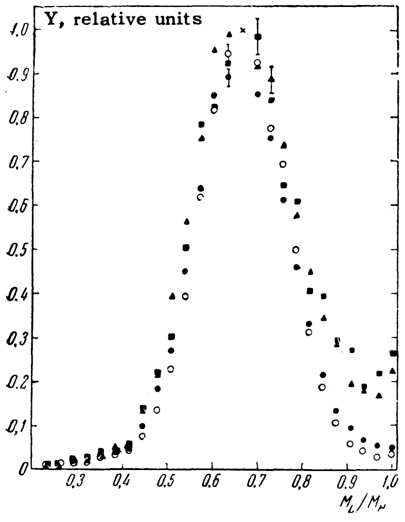

FIG. 1. Experimentally measured dependence of the fragment yield on the mass ratio of the light and heavy fragments: ○ – thermal neutrons; ●, ▲, ■ – neutrons with energies 7, 14.5, and 20 MeV, respectively.

The results of the measurements of the average kinetic energy E_k^S, calculated from the distributions of the pulse amplitudes for the symmetrical fission, are listed in the table. The first column of the table indicates the energy of the neutrons causing the fission, and the second indicates the ratio $\bar{\rho}$ of the measured average kinetic energies in the symmetrical type of fission and in fission by thermal neutrons, for the entire mass spectrum; in the latter case it amounts to 155 MeV without account of the ionization defect. In the following four columns are given the corrections for the resolution of the apparatus $\Delta\rho_1$, for the effect of motion of the center of mass $\Delta\rho_2$, for the increase in the number of prompt neutrons emitted during fission $\Delta\rho_3$, and for the ionization defect $\Delta\rho_4$. These are followed by the final values of ρ and the values of the average kinetic energy for symmetrical type of fision (E_k^S) and for the total mass distribution (E_k). The errors indicated in the table take into account the error in the measurement of $\bar{\rho}$ and the uncertainty connected with the introduction of the corrections. The results obtained at 14.5 MeV are in good agreement with data by others, namely 163 [8] and 161 MeV [9]. The energies corresponding to the total mass

E_n, MeV	$\bar{\rho}$	$\Delta\rho_1$**	$\Delta\rho_2$	$\Delta\rho_3$	$\Delta\rho_4$	ρ	E_k^s, MeV	E_k, MeV
7*	0.912	0.092	0.009	0.005	0.080	1.098	170±7	170±3
14.5	0.937	0.014	0.017	0.009	0.080	1.057	164±3	168±3
20	0.916	0.010	0.021	0.013	0.080	1.040	161±3	164±3

*For the total mass distribution the mean value of the energy of the neutrons causing the fission is approximately 5 MeV.

**In order to correct for the finite energy resolution Δ_ρ, we have used the distributions obtained in this work of the mass and of the kinetic energy of the fragments in fission caused by thermal neutrons.

distribution are also in agreement with the results of Okolovich and Smirenkin [13].

DISCUSSION OF MEASUREMENT RESULTS

The results of the present paper show that the average kinetic energy of the fragments (E_k^S) remains constant in symmetrical fission as the energy of the fission-inducing neutrons varies from 7 to 20 MeV, just as in asymetrical fission. Thus, the present experiment refutes the hypothesis of Selitskiĭ and Éĭmont [4] that the symmetrical type of fission, unlike the asymmetrical one, is fast and the excess excitation energy of the compound nucleus goes over not into fragment excitation energy but into fragment kinetic energy. The hypothesis advanced by Kovalenko, Petrzhak, and Adamov [9] can likewise not be reconciled with the results of our experiment.

The difference in the values of E_k at fragment mass ratio $M_L/M_H \sim 1$, obtained in experiments with fast and thermal neutrons, can be explained by the following considerations. It is natural to assume that the two independent types of fission—asymmetrical and symmetrical—correspond to different fission barriers. Johansson [14] has shown, by taking into account the role of the individual nucleons, that the thresholds corresponding to symmetrical and asymmetrical types of fission differ greatly, and that for the compound nucleus U^{236} the difference between them is approximately 2.5 MeV. It can also be assumed, following Johansson, that the nuclear configurations at the saddle points are also different, being pear shaped in the case of asymmetrical fission and having a shape with mirror symmetry in the case of symmetrical fission. In the case of fission through a symmetrical barrier, the value of E_k^S for thermal neutrons is the same as for E_n = 7—20 MeV. On the other hand, the experimentally observed values E_k = 140 MeV for thermal-neutron fission with $M_L/M_H = 1$ must be classified as fission through an asymmetrical saddle point. When the excitation energy of the compound nucleus corresponds to fission by thermal neutrons, the symmetrical type of fission is subbarrier and makes a very small contribution to the total fragment yield at $M_L/M_H \sim 1$.

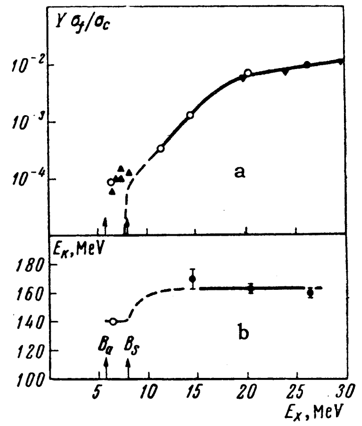

FIG. 2. a – dependence of the quantity $Y\sigma_f/\sigma_c$, which is proportional to the relative probability of symmetrical fission, on the excitation energy E_x of the compound U^{236} nucleus: ▼– data of [1], ●– [15], ▲– [16], ○ – present work. The arrows designate the values of the barrier heights B_s and B_a for symmetrical and asymmetrical fission. Dashed curve – approximate variation of the quantity $Y\sigma_f/\sigma_c$ with account of the penetrability of the barrier for symmetrical type of fission; b – dependence of the energy E_k on the excitation energy of the compound nucleus E_x: dashed curve – proposed course of the quantity $E_k(1) = E_k^a(1)Y_a(1) + E_k^s Y_s$, calculated under the assumption that E_k^a and E_k^s are independent of E_x.

Figure 2a shows the dependence of $Y\sigma_f/\sigma_c \sim \Gamma_s/\Gamma$, which is proportional to the fission width for the symmetrical region, on the excitation energy E_x of the compound nucleus U^{236} (Y is the yield of symmetrical fissions [1,15,16], σ_f and σ_c are the total fission cross section and the cross section for the formation of the compound nucleus, while Γ_s/Γ is the ratio of the width of symmetrical fission to the total width of the inelastic processes). It is seen from the figure that extrapolation of the dependence of Γ_s on E_x to the excitation energy for thermal-neutron fission, even without account of the penetrability of the barrier, gives a value which is much smaller than the corresponding observed quantity. The same figure shows the approximate theoretical course of this dependence under the barrier. Beneath, in Fig. 2b, is shown the assumed dependence of the average kinetic energy $E_k(1)$ on E_x in the region $M_L/M_H \sim 1$, plotted with account of the yields Y_s and $Y_a(1)$ and the values $E_k^s = 163$ and $E_k^a(1) = 140$ MeV for the symmetrical and asymmetrical types of fission.

The fact that in the case of fission by thermal neutrons the yield, for $M_L/M_H \sim 1$, is almost completely connected with the fission through an asymmetrical saddle point, in which the fissioning nucleus has a finite probability of breaking up into nearly equal masses during the course of descending from the top of the barrier, owing to the dynamic effect, is also confirmed by the experiments of Cunningham et al [16]. The results of these measurements (see Fig. 2a) have shown that in the neutron energy range from thermal to 1 MeV the yield of symmetrical fissions changes little and does not correspond to the variation that is characteristic for symmetrical type of fission.

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