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Abstract

Full Text

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ASYMMETRY AND ANGULAR ANISOTROPY OF THE MASS DISTRIBUTIONS OF FISSION FRAGMENTS OF U^{238} BY NEUTRONS WITH AN ENERGY OF 14 MeV

In work (^{1}) it was noted that, in the fission of U^{238} nuclei by neutrons with an energy of 14 MeV, a dependence is observed of the fragment mass distribution on the angle θ between the direction of the neutron beam and the direction of fragment emission. From Fig. 1 it is seen that the total yield of fragments at $0^\circ \leq \theta \leq 34^\circ$ is greater than at $70^\circ \leq \theta \leq 80^\circ$, i.e., an angular anisotropy of the fragment yield is observed. In addition, at small θ a noticeable increase in the fragment yield is observed at values $R \geq 1.45$ (R is the ratio of the mass of the heavy fragment to the mass of the paired light fragment). The value of the anisotropy, averaged over all R, determined experimentally as the ratio of the total fragment yield at $0^\circ \leq \theta \leq 34^\circ$ to the yield at $70^\circ \leq \theta \leq 80^\circ$, is 1.40 ± 0.05. The dependence of the angular anisotropy on R, obtained experimentally, is shown in Fig. 1. An analogous dependence was observed by the authors of work (^{2}). In work (^{3}) it was indicated that, at a sufficiently high energy of the bombarding particles, the resulting anisotropy and the relation of the angular anisotropy to mass asymmetry may be caused by the superposition of the mass distributions of fragments of nuclei fissioning after the emission of neutrons: nuclear reactions (n, nf), $(n, 2nf)$, etc. The threshold neutron energies for the (n, nf) and $(n, 2nf)$ reactions for U^{238} are, according to (^{4,5}), respectively 5.9 and 12.1 MeV. When a U^{238} nucleus absorbs neutrons with an energy of 14 MeV, if the captured neutron and the emitted neutrons are taken into account, the fission of three differently excited nuclei will actually be observed: U^{239}, U^{238}, and U^{237}.

The dependence of the total fission cross section σ of U^{238} on the neutron energy E_n has a step-like form (^{6,7}). The first step σ_0 corresponds to fission of the compound nucleus U^{239} without preliminary neutron emission, the second σ_1 —after emission of one neutron, the third σ_2—after emission of two neutrons, etc. The step-like dependence of σ on E_n makes it possible to determine the numerical values $\sigma_0, \sigma_1, \sigma_2$ and to assume that these quantities do not depend on E_n. Obviously, on the basis of the step-like character of the curve σ, one may consider that

$$\sigma = \sigma_0 + \sigma_1 + \sigma_2. \tag{1}$$

It follows from formula (1) that the fraction of fragments from fission of the nuclei U^{239}, U^{238}, U^{237} will be respectively σ_0/σ, σ_1/σ, σ_2/σ.

Theory (^{3}) gives for the angular anisotropy the expression

$$w(0^\circ)/w(90^\circ) = 1 + I_{\max}^2/8k_0^2, \tag{2}$$

where $I_{\max}$ is the maximum angular momentum of the fissioning nucleus, the parameter $k_0^2 = J_{\text{eff}}T/\hbar^2$, J_{eff} is the effective moment of inertia, and T is the nuclear temperature.

Fast neutrons absorbed by the even-even nucleus U^{238}, according to (^{3}), introduce an angular momentum determined from the relation $I_{\max}^2 = 5E_n$, i.e., in our case $I_{\max}^2 = 70$. Since neutrons are emitted by the excited nucleus from an S-state, the entire angular momentum introduced by the external neutron in the nucleus, remains in it. Thus, the angular momentum of all nuclei U^{239}, U^{238}, and U^{237} may be considered the same. The values of the parameter

Table 1

Fission reactions under bombardment of U^{238} with 14 MeV neutrons	Fissioning nucleus	Fission-reaction cross sections σ_i, barn	Relative contribution of the reaction $\frac{\sigma_i}{\sigma}100$, %	Excitation energy above the fission threshold E_i^*, MeV	Parameters k_{0i}^2	Angular anisotropy a_i	Resulting anisotropy $A = \sum \frac{\sigma_i}{\sigma} a_i$
(n, f)	U^{239}	0.567	48.6	13.2	79	1.1	1.43
(n, nf)	U^{238}	0.433	37.1	8.2	32	1.27	1.43
$(n, 2nf)$	U^{237}	0.167	14.3	2	4.3	3.04	1.43
		$\sigma = \sum \sigma_i = 1.167$	100%				

k_0^2 depend on the excitation energies E^* above the fission threshold and on the evenness of the nuclei (8). They were determined on the basis of the data of Refs. (8, 9). Table 1 gives the values of σ_i, σ_i/σ, E_i^*, k_{0i}^2, and the anisotropy values calculated from formula (2) for the nuclei U^{239}, U^{238}, and U^{237} participating in fission.

If the angular anisotropies for each nucleus are denoted by a_i, then, as is not difficult to show, the resulting anisotropy can, to a sufficiently good approximation, be estimated from the formula

$$A = \frac{\sigma_0}{\sigma} a_0 + \frac{\sigma_1}{\sigma} a_1 + \frac{\sigma_2}{\sigma} a_2. \tag{3}$$

It should be noted that the experimental value of the anisotropy $A = 1.40 \pm 0.05$ is very close to the value $A = 1.43$, calculated from formula (3). This circumstance led to the idea of explaining the anomalous course of the fragment-yield curve at $R \geq 1.45$ and the dependence of the anisotropy on R (Fig. 1) by superposition of the mass distributions of the fission fragments of the nuclei U^{239}, U^{238}, and U^{237}. We used tabulated radiochemical data (10). In doing so, the following assumptions were made:

1. The fragment-yield data for fission of U^{238} by neutrons of the fission spectrum may be used instead of the missing data for fission of U^{239} with $E^* = 13.2$ MeV.
2. The fragment-yield data for fission of U^{238} by 10 MeV photons may be used as data on fission of U^{238} with $E^* = 8.2$ MeV, and the data for fission of U^{235} by thermal neutrons instead of the missing data on fission of U^{237} with $E^* = 2$ MeV.
3. For a given nucleus, the angular anisotropy does not depend on R.

Fig. 1. Mass distributions of fragments and dependence of the angular anisotropy on the fragment mass ratio R in fission of U^{238} by 14 MeV neutrons. Solid lines—experimental data; dashed lines—calculated. 1—$0^\circ \leq \theta \leq 34^\circ$; 2—$70^\circ \leq \theta \leq 80^\circ$.

Having thus determined the yields of fission fragments of the nuclei U^{239}, U^{238}, and U^{237} and knowing the contribution from fission of these nuclei to the total yield and their anisotropy (Table 1), we constructed relative fragment yields for the case of fission of U^{238} by 14 MeV neutrons as functions of R for $\theta = 0^\circ$ and $\theta = 90^\circ$, and then calculated the anisotropy values at various R (Fig. 1, dashed lines). As is seen from Fig. 1, good agreement of the experiment is observed—

···of the experimentally measured and calculated fragment mass distributions, and also of the experimental and calculated dependences of the anisotropy on R.

The results of the calculations performed and their good agreement with the experimental data show that:

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A. The calculated effect of a considerable increase in the yield of fragments with $R \geqslant 1.45$ in the direction of the neutron beam, as well as the effect of the connection between the anisotropy and R, are expressed quite clearly and could not have been masked by inaccuracies caused by the assumptions we made.

B. The idea of the authors of Ref. (3) concerning the reasons for the connection between the angular anisotropy and R at energies of the bombarding particles exceeding the thresholds for emissive fission corresponds to reality for the case under discussion of fission of U^{238} by 14-MeV neutrons.

C. The formula (2) obtained theoretically for the anisotropy is confirmed by the totality of the experimental data used in this work.

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