The Angular Distribution of Fragments from Fission of Uranium at High Excitation Energies

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(Submitted to JETP editor May 12, 1955)
J. Exper. Theoret. Phys. USSR **29**, 292-295 (September, 1955)

We have investigated the fission of uranium in P-9 fine-grained nuclear emulsions, soaked in aqueous solutions of uranium salts and irradiated with 660 mev protons. The angular distribution of fission fragments relative to the direction of the proton beam was studied at excitation energies of the uranium nucleus ~ 75, 150 and 300 mev. The angular distribution of the fragments can be described approximately by the function $a + b\sin^4\varphi$. The anisotropy increases somewhat with increasing excitation energy.

INTRODUCTION

THE presently available experimental data on angular distribution of fragments from the fission of heavy nuclei show that there is an appreciable anisotropy in the distribution of fragments relative to the direction of the beam of particles producing the fission. The character of this anisotropy depends essentially on the type of particle interacting with the nuclei.

Already in 1953 it was shown, in work carried out in our laboratory[1], that there is an appreciable anisotropy in the angular distribution of fragments from fission of uranium by 460 mev protons. The ratio of the number of fragments in the direction of the beam and perpendicular to it is substantially less than unity. Roughly the same type of anisotropy was observed in the photofission of thorium[2]. In this case the angular distribution can be expressed as

$$I(\varphi) = a + b\sin^2\varphi,$$

where φ is the angle measured from the direction of the gamma ray beam.

Later there appeared reports in the literature of investigations of the angular distribution of fragments from fission of uranium and thorium by neutrons from thermal energy up to 20 mev, and by 22 mev protons. It was shown[3] that for fission of thorium by 22 mev protons the angular distribution is satisfactorily described by a formula of the type $I(\varphi) = a + b\cos^2\varphi$, where the ratio b/a increases with increasing ratio of mass of the fission fragments. In addition, the dependence of the angular distribution of fission fragments on the energy of the incident neutrons was investigated[4]. For fission by neutrons with energy 10^{-7}; 2.5; 4.6; 7.5; 14.3; and 20.4 mev, the ratios of yields of fragments at angles 0° and 90° were: 0.99; 1.02; 1.13; 1.36; 1.27; 1.11. Thus, as the neutron energy is increased in this range, the anisotropy first increases and then decreases, but for all energies in this interval the angular distribution is described by the formula

$$I(\varphi) \sim (1 + a\cos^2\varphi + b\cos^4\varphi).$$

In the present work we studied the angular distribution of fragments from fission of uranium by 660 mev protons.

EXPERIMENTAL DATA

The angular distribution of fragments from fission by 660 mev protons was studied using thick-layered emulsions. Fine-grained nuclear emulsions, type P-9, (prepared in the laboratory of N. A. Perfilov), were soaked in a solution of uranium salt and irradiated with a beam of protons. The developed plates were searched for cases of fission of U, and the projected angles between the direction of emergence of the fragments and the direction of the proton beam were measured. Then, to separate cases of fission with a definite excitation energy, the number of charged particles accompanying the fission was counted. As was shown previously[5], a given number of charged particles from fission is associated with a definite average angle between

[1] V. I. Ostroumov, Otch. RIAN (Report of Radium Inst., Acad. Sci., USSR) 1953

[2] E. J. Winhold et al, Phys. Rev. **87**, 1139 (1952)

[3] B. I. Cohen et al, Phys. Rev. **94**, 625 (1954)

[4] J. E. Brolley et al, Phys. Rev. **95**, 651 (1954)

[5] V. P. Shamov, Otch. RIAN (Report of Radium Inst., Acad. Sci., USSR) 1954

the two fragments, and consequently, with a definite excitation energy of the fissioning nucleus.

Table I gives the results of measurement of the angular distribution of uranium fission fragments for high excitation energies.

TABLE I

Angle interval (degrees)	Number of fissions accompanied by n charged particles		
	$n=0$, $E\approx 60$ mev	$n=1$, $E\approx 150$ mev	$n\geq 2$, $E\approx 320$ mev
0—10	114	59	85
10—20	119	60	81
20—30	124	61	63
30—40	130	60	70
40—50	123	70	93
50—60	123	77	96
60—70	134	73	90
70—80	139	77	104
80—90	132	87	114

Figure 1 is a histogram of the angular distribution of all observed cases of fission.

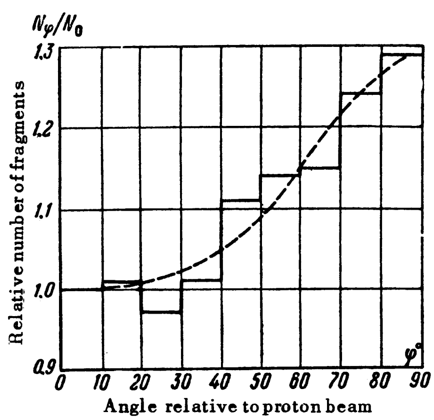

FIG. 1. Angular distribution of uranium fission fragments with respect to the direction of the 660 mev proton beam. The dotted curve is the function $N_\varphi/N_0 = 1 + 0.29 \sin^4 \varphi$

DISCUSSION OF RESULTS

If we try to describe the angular distribution shown in Fig. 1 by a function of sin φ, then we see that the function must contain at least the fourth power of sin φ. The dotted curve in Fig. 1 shows the variation $N_\varphi/N_0 = 1 + 0.29 \sin^4 \varphi$.

With increasing excitation energy, the angular distribution changes very slowly, and the anisotropy increases somewhat. If we express the anisotropy as the ratio of the number of fissions in the interval 60-90° to the number of fissions in the interval 0-30°, we get the following variation in the anisotropy (Table II).

TABLE II

E_{exc} (mev)	~60	~150	~320
Anisotropy $\frac{N_{\varphi>60°}}{N_{\varphi<30°}}$	1.13 ± 0.1	1.31 ± 0.15	1.35 ± 0.16

All our statements refer to the distribution of projections of fission fragment tracks on the plane of the emulsion. As for the spatial distribution of the fragments, we should point out that the ansiotropy of the distribution per unit solid angle, along the beam and perpendicular to it, will be even somewhat greater than the anisotropy in the distribution of the projections.

If we look at the whole range of nuclear excitation energies for irradiation with nucleons, we can plot the dependence of the anisotropy of the distribution on excitation energy (Fig. 2).

We find it difficult at present to explain either the shape of the angular distribution of fragments or its dependence on excitation energy. There undoubtedly is some explanation for the fact that there is a well-defined narrow range of energy within which the anisotropy of the fission fragment distribution reverses its character. We should mention another important fact. As shown by other work[6], there is a definite connection between the excitation energy of the uranium nucleus and the range distribution of the fragments. With increasing excitation energy of the uranium nucleus, the asymmetry in the distribution of fission fragment ranges increases. Thus, simultaneously with the increase in anisotropy of fission relative to the direction of the incident proton beam there is an increase in the contribution of the asymmetric form of nuclear fission. This variation is clear from Table III.

In conclusion, we should note that one may speculate that the observed anisotropy in the angular distribution of fission fragments and its

[6] V. P. Shamov and O. V. Lozhkin, Otch. RIAN (Report Radium Inst., Acad. Sci., USSR) (1955); J. Exper. Theoret. Phys. USSR 29, 286 (1955); Soviet Phys. 2, 111 (1956)

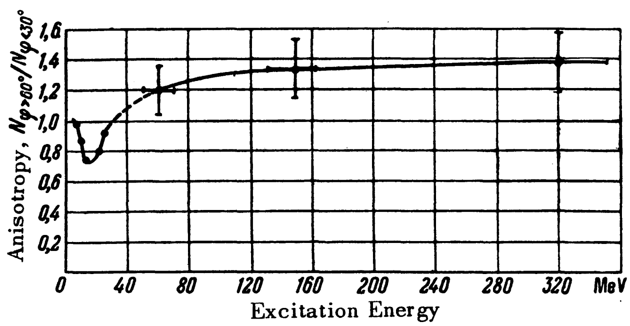

FIG. 2. Dependence of the anisotropy in distribution of fragments from fission of uranium on the excitation energy of the nucleus. The initial part of the curve is taken from the data of reference 4.

TABLE III

E_{exc} (mev)	~60	~150	~320
Anisotropy in angular distribution: $\frac{N_{\varphi>60°}}{N_{\varphi<30°}}$	1.13	1.31	1.35
Asymmetry in range of fragments: $\frac{N(l_l/l_h>1.45)}{N(l_l/l_h<1.15)}$	0.28	0.45	0.86

relation to the asymmetry of fission may be directly connected with the very mechanism of the fission process, and therefore deserves most careful study.

Translated by M. Hamermesh
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