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Letters to the Editor

THE MEASUREMENT OF THE SPECTRA OF FISSION NEUTRONS FROM U^{233}, U^{235}, AND Pu^{239} IN THE 50 – 700 kev RANGE

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THE spectra of fission neutrons have been measured by means of a cloud chamber, filled with water vapor and hydrogen to a pressure of 210 mm of mercury. The sources of fission neutrons were samples of mixed oxides of uranium and plutonium dioxide, prepared in the form of disks 60 mm in diameter and 2.5 mm thick, and irradiated by a beam of thermal neutrons from a reactor.

The cloud chamber was placed out of the beam at a distance of 16.5 cm from the sample. The chamber of 20 cm diameter and of 6 cm depth was constructed so as to have a minimum of neutron scattering material. The beam of thermal neutrons was interrupted by a fast-acting mechanical screen of boron carbide. The screen was opened in synchronization with the expansion of the chamber. Experimentally, on the average, there were approximately 10 proton recoil tracks per expansion. The background of fast neutrons from the reactor was less than 2%. Approximately 30,000 proton recoil tracks were obtained for each sample.

The lengths of the proton recoil tracks making an angle < 15° with the neutron direction were measured during the analysis of the results. The pictures were analyzed by stereoscopic projection. The region covered had a diameter of 17 cm and a height of 4.5 cm.

The distribution of the recoil protons, terminating in the gas of the chamber, by energy intervals, is given in the table. The lower limit of the measured energy is 50 kev which corresponds to a track length of 0.8 cm. Tracks shorter than 0.8 cm were easily observed on photographs, but it was difficult to measure them with sufficient accuracy.

In converting from a spectrum of proton recoils to a spectrum of neutrons, it is necessary to take into account the dependence of the neutron-proton scattering cross section on energy, and the geometric correction, in the probability P that tracks of varying lengths will terminate in the chamber. The scattering cross section and the term 1/P by which the number of tracks must be multiplied are displayed in the table.

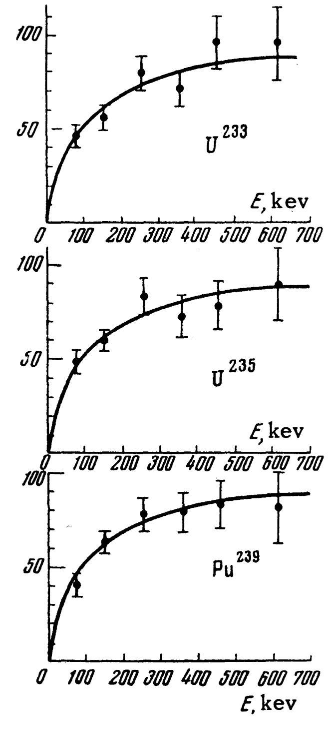
ΔE, kev	Track length in cm	Number of tracks			σ, bn	$\frac{1}{P}$
		U^{233}	U^{235}	Pu^{239}		
50—100	0.8— 1.3	59	62	51	14.0	1.10
100—200	1.3— 2.5	111	118	124	11.5	1.15
200—300	2.5— 4.5	103	109	102	9.1	1.37
300—400	4.5— 6.9	60	61	67	7.6	1.81
400—500	6.9— 9.6	49	39	41	6.5	2.62
500—700	9.6—16.2	32	30	27	5.6	6.74

The fission neutron spectra are presented in the figure.

Comparing the experimental data in the table and in the figure, one can see that the fission neutron spectra from U^{233}, U^{235}, and Pu^{239} in the measured region coincide within the experimental errors (10 to 20%), and satisfactorily approximate Watt's formula[1]

$$F(E) \sim e^{-E/T} \sinh \left(2\sqrt{\omega E}/T\right) \qquad (1)$$

for values of the parameters $\omega = 0.5$ Mev and $T = 1$ Mev.



Spectra of the fission neutrons from U^{233}, U^{235}, and Pu^{239}. The experimental points are given in the form of relative number of neutrons per 100-kev energy interval. The full lines correspond to formula (1).

The low energy region of the U^{235} fission spectrum was measured earlier with a cloud chamber by Bonner et al.[2] and by Barton.[3] Within the limits of error (15 to 20%), these authors also obtained agreement between the form of the spectrum and curve (1).

In our earlier work,[4] estimates were obtained of the temperatures of fragments from U^{233} and Pu^{239} relative to U^{235}, equal to (1.04 ± 0.01) and (1.05 ± 0.01) Mev. The value of the function F(E) for parameters $\omega = 0.5$ Mev, $T_0 = 1$ Mev, $T_1 = 1.03$ Mev, $T_2 = 1.06$ Mev in the spectrum energy region 0 — 1 Mev differ from each other by not more than 4%, which is less than the accuracy of our measurements.

In this work, we also determined the ratio of the number of recoil protons in the interval 0.05 — 0.6 Mev to their number with energies > 0.6 Mev was also determined. The experimental values of the ratios for U^{233}, U^{235}, and Pu^{239} are respectively equal to 0.49 ± 0.04, 0.53 ± 0.04, and 0.48 ± 0.04. A calculation using formula (1) and the parameter values given above gave for these values the numbers 0.5, 0.52, and 0.495.

Thus, the measurements of fission neutron spectra in the region of low energies are in agreement with the results of Ref. 4, confirming the conclusion that the previously noted difference in the fission neutron spectra of U^{233}, U^{235}, and Pu^{239} lies in the high energy region.

In conclusion I express my gratitude to I. I. Bondarenko and O. D. Kazachkovski for suggestions and discussion of the results and to A. I. Leipunskii for his continued interest in this work.

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[2] Bonner, Ferrell, and Rinehart, Phys. Rev. **87**, 1032 (1952).

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SYSTEMATICS OF THE AVERAGE NUMBER ν OF PROMPT FISSION NEUTRONS

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THE number ν of prompt neutrons emitted during fission, is determined by the energy balance equation

$$E_f = E_k + E_x = E_k + \nu E_n + E_\gamma, \tag{1}$$

in which E_f is the fission energy, E_k and E_x are the kinetic and the excitation energies of the pair of fragments, and νE_n and E_γ are the energies carried by the prompt neutrons and γ rays respectively. In this work we compare the experimental values of ν (Refs. 1 — 8) with the results of calculations based on the assumptions that will be discussed below.

We considered the masses of only two fragments, a light one M_ℓ and a heavy one M_h, corresponding to the most probable method of fission. When calculating the fission energy, the mass of the fissioning nucleus M(A, Z) was determined from the Green[9] semi-empirical formula, and the masses of the fission fragments $M(A_\ell, Z_\ell)$, $M(A_h, Z_h)$ were calculated by the Fermi formula with the Fong correction factors,[10] which take into account the shell structure of the nuclei. Since the mass of the heavy fragment varies slightly[11] over the wide range $232 < A < 252$, owing to the shell effect, and has an average value 139 ± 3, we assumed for simplicity $A_h = 140$ (prior to the neutron emission). The values of Z_ℓ and Z_h, the initial charges of the fission fragments, are calculated subject to the hypothesis of equal β-decay chains.

The kinetic energy E_k of the fission fragments was calculated from the formula

$$E_k = c_1 Z^2 A^{-1/3}(1 - c_2 Z^2 / A), \tag{2}$$

obtained by representing E_k as the Coulomb repulsion energy of two charged deformed spheres.[10] The constants c_1 and c_2 are chosen to obtain the best fit between Eq. (2) and the experimental values of ν in Eq. (1).

The average energy E_n carried by a prompt neutron consists of the binding energy E_b of the last neutron in the fragment and its mean kinetic energy 2T with respect to the fragment at rest. The temperature T of the fragment, after the emission of the neutron, was estimated from data on the neutron spectra of the fission of U^{233}, U^{235}, and Pu^{239} by thermal neutrons[12] and the spontaneous fission of Cf^{252} (Ref. 13). The values of E_b were calculated from the mass formula of Fermi-Fong.[10] The value $\nu_\ell / \nu_h = 1.3$, obtained by Fra-