A STUDY OF THE ENERGY AND ANGULAR DISTRIBUTIONS OF NEUTRONS EMITTED IN THE FISSION OF U^{235} INDUCED BY THERMAL NEUTRONS

M. V. BLINOV, N. M. KAZARINOV, and A. N. PROTOPOPOV

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The energy spectra of neutrons, emitted at the angles of 0, 45, and 90° to the direction of flight of fragments in the fission of U^{235} by thermal neutrons, were measured. The neutron emission probability ratio at 0, 45, and 90° was found to be 5.7 ± 0.2) : (2.9 ± 0.1) : 1.

A study of the characteristics of emission of "prompt neutrons" in nuclear fission yields valuable information that explains the fission mechanism.

In many of the papers referred to in the reviews,[1,2] the fission neutrons of several nuclei were carefully measured. These data, and also the measurements of the neutron angular distributions[3,4] pointed to the emission of neutrons from the scattered fragments. The calculations of Terrell,[2] who assumed that the fission neutrons are emitted via the usual mechanism of neutron evaporation from the excited nuclei, have shown that this assumption generally does not contradict the experimental data. Wilson[3] and Fraser[4] determined the angular distributions of the neutrons for the entire energy spectrum as a whole. Others have measured the integral energy spectra averaged over all neutron emission angles.

An interpretation of the data obtained in such experiments aimed at gaining information on the angular and energy distributions in the fragment system is quite difficult. In this connection it is desirable to set up experiments in which the averaging over the angles would be eliminated from the measurements of the energy spectra.

The present work was undertaken to measure the energy distribution and to determine the number of neutrons emitted at different fragment flight angles (0, 45, and 90°) in fission of U^{235} by thermal neutrons.

MEASUREMENT PROCEDURE

The thermal neutron beam was intercepted by a gas fission-fragment scintillation counter, in which a thin aluminum plate coated on both sides with U^{235} was placed. The density of these layers was ~ 2 mg/cm^2. Collimators, which determined the most probable fragment emission angle, with a scatter of ± 10°, were placed on the layers. The gas counter was filled with pure xenon to a pressure of 1.5 atm. A scintillation fission-neutron detector was located at a definite distance from the fissioning layer, at different angles to the fragment direction. The detector was a stilbene crystal 30 mm in diameter and 20 mm thick used in conjunction with a photomultiplier. The neutron energy was determined from the transit time between counters. In most measurements this distance was 50 cm. The transit time was determined with the aid of a 100-channel time analyzer, based on principles analogous to those indicated by Garg.[5]

The time photomultipliers were of the FÉU-33 type. The half-width of the distributions of Co^{60} γ quanta from two chosen photomultiplier pairs was found to be 6×10^{-10} sec. In order for the apparatus to be able to count low-energy neutrons, the photomultipliers were selected for maximum pulse current and for minimum noise. The neutron registration threshold energy was about 100 keV. The energy dependence of the neutron counter efficiency was determined by comparing the well known neutron spectrum of U^{235} fission[1,2] with the experimental spectrum measured in the present investigation using a uranium layer without a collimator. These measurements were repeated several times to account for the variation of the threshold due to the "fatigue" of the photomultiplier.

A considerable portion of the time scale of the spectrometer was calibrated against the transit time of the γ quanta over distances ranging from 0 to 24 m (~ 80 nsec). The remaining part of the scale was graduated by means of calibrated segments of RK-2 cable. The width of the analyzer channel could be varied from 1 to 2 nsec. The linearity of the scale was determined periodically during the course of the measurements, both from the change in the delay of one of the channels and from the random pulse coincidences in the two counters. Deviations from linearity did not exceed 3%. To measure the linearity by the random-coincidence method, the neutron counter was placed sufficiently far from the fission counter to exclude the possibility of true coincidences. The required load on the neutron channel was selected with the aid of the neutron source. The fragment counter was situated in the neutron beam, as before, and registered uranium fission events. If the spectrometer scale is strictly linear, the time widths of all the channels are identical and each channel receives in the mean the same number of coincidence pulses. The time distribution of the random coincidences will then be rectangular.

The null of the time scale was determined from the position of the fission gammas, with account of the corrections for the transit time of the base gammas and for the average delay in the emission of the γ rays compared with the fission event. [6] The resolution time was determined in the measurement of the neutron spectra from the width of the γ peak, and amounted to 5 nsec. The deterioration in the resolution time observed in these experiments, compared with the measurements of the coincidences of the Co^{60} γ quanta, was caused by the strong reduction in the registration threshold and, apparently, also by a certain smearing of the γ peak due to the scatter in the time of delay in the emission of the fission γ quanta. [6]

We registered during the measurements some 10^5 fission fragments per minute, and the neutron count was $(2-5) \times 10^4$ per minute. Almost all the neutron counter readings were due to the registration of background γ rays and fast neutrons. The high load on the neutron channel made the random-coincidence background appreciable. The maximum background was obtained in measurements at an angle of 90° and did not exceed the number of true coincidences at the limits of the measured interval. The loads in the branches were fixed during the experiment, and knowing the resolution time of one channel it was possible to calculate the random-coincidence background.

An exceedingly vital problem is that of the possible spectrum distortion due to the entry of scattered fission neutrons into the detector. The closest effective neutron scatterer was the floor, one meter away. To determine the distortion of the spectrum we made several control experiments, consisting of measuring the neutron spectrum at different distances from the fissioning layer (from 25 to 75 cm) at different distances from the floor (50, 100, and 150 cm). The control experiments showed no change in the spectra within the limits of statistical errors.

The neutron detector was covered with a lead shield to decrease the γ-ray background; in some experiments the shield was 1.5 mm thick and in others 10 mm. The efficiency of the neutron count was measured in each case. No essential differences were observed in the character of the energy spectra for these two cases.

The number of fissions due to neutrons passing through the cadmium filter did not exceed 2% of the number of fissions in the thermal-neutron beam.

MEASUREMENT RESULTS

Figures 1 and 2 show the U^{235} fission neutron transit-time distributions, measured at 0 and 90° to the fragment direction. In processing these data, we subtracted the background of random coincidences, introduced a correction for the neutron-counter efficiency, and converted to an energy scale.

Figure 3 shows the U^{235} fission neutron energy spectra obtained in this manner for 0, 45, and 90°. The spectrum maximum E_{max} for $\varphi = 0°$ is in the region 1.6—1.7 MeV, while the mean spectrum energy $\bar{E}$ is near 2.2 MeV. The probabilities of neutron emission at different angles are related as $N(0°) : N(45°) : N(90°) = (5.7 \pm 0.2) : (2.9 \pm 0.1) : 1$.

After the present investigation was set up, Nefedov [7] published his measurements results on the spectra and fragment-neutron angle correlation in the fission of U^{235}. Our neutron-energy

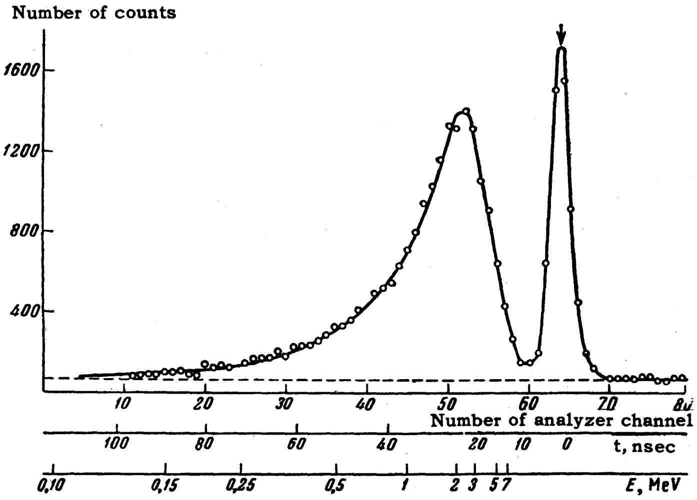

FIG. 1. Transit-time distribution of U^{235} fission neutrons, measured at 0° to the fragment direction. The transit base here and in Fig. 2 was 50 cm; the arrow designates the peak due to fission γ rays. The dashed line shows the random-coincidence background spectrum.

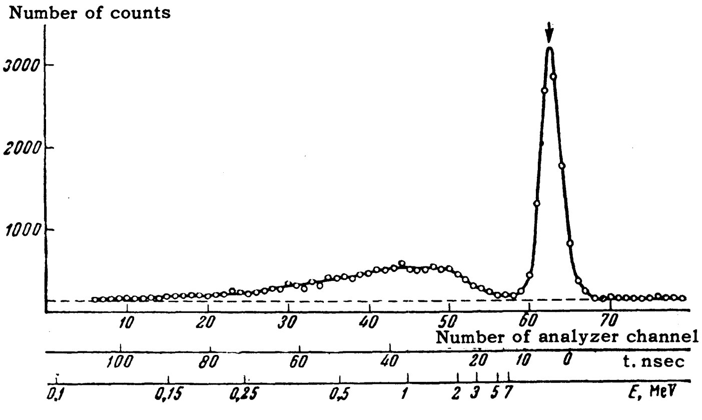

FIG. 2. Distribution of U^{235} fission neutrons by transit time, measured at 90° to the fragment direction.

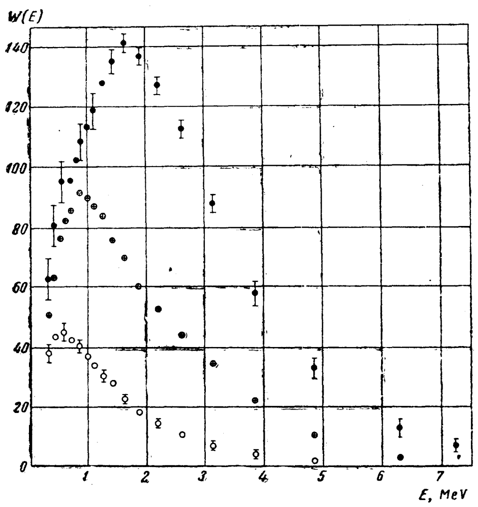

FIG. 3. Energy spectra of U^{235} fission neutrons emitted at 0° (●), 45° (⊕), and 90° (○) to the fragment direction. The errors indicated include statistical uncertainties and straggling between series of measurements. The spectra have been reduced to the same number of fissions.

spectra for 45 and 90° turned out to be harder, and the spectrum for 0° much harder, than those of Nefedov,* whose measurements were also made with thermal neutrons.

It can be noted at the same time that the spectra obtained in the present investigation differ little (except when $\varphi = 90°$) from the similar data obtained by Vasil'ev et al [8] in experiments with 14-MeV neutrons. The mean neutron energy for $\varphi = 0°$ is approximately the same in our experiments as in [8]. If we recognize that our collimation angle was smaller than that of Vasil'ev, then for $\varphi = 0°$ the neutron fraction obtained for the same interval of fragment emission angles in fission by thermal neutrons is somewhat softer than that for 14-MeV neutrons. This agrees with the expected variation of the neutron energy due to the difference in the excitation energy of the primary nucleus. [9]

The angular distribution of neutrons in thermal-neutron fission of U^{235} was investigated by Wilson, [3] Fraser, [4] and Nefedov. [7] The ratio of the number of neutrons emitted at 0° to the number of neutrons at 90°, obtained in the present work and equal to 5.7, is close to the results of Wilson (5.8) and Nefedov (5.9), and differs somewhat from those of Fraser (4.4). In fission by 14-MeV neutrons [8] the ratio $N(0°) : N(90°) = 4.0$ implies a more isotropic distribution of the fission neutrons in the laboratory system (l.s.).

It is interesting to compare our experimental results with the calculated data. Unfortunately, spectra for definite neutron-emission angles were calculated only by Vasil'ev et al [8] under assumptions that in the rest frame of the fragment the emission is isotropic in the angles and Maxwellian in the energies.

Our experimental data for the energy and angle distributions of the neutrons in the laboratory system do not correspond to the calculated results for any of the fragment temperatures employed (0.2, 0.6, and 1 MeV). An analogous conclusion was drawn by Vasil'ev [9] for fission of uranium by 14-MeV neutrons. It must be noted that the use of intermediate values for the temperature does not improve the convergence of the results. It is still premature, however, to draw on this basis any conclusions regarding the fission-neutron distribution in the fragment reference frame, since the calculations were made under various simplifying assumptions. The authors of [8] have reported that they are continuing their calculations with account of the fragment excitation energy distribution in accord with the results of [2]. The more exact calculations may improve the agreement with experiment.

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*It follows from Nefedov's neutron-energy distributions[7] that $E_{max} \approx 0.8-0.9$ MeV and $\bar{E} \approx 1.6$ MeV for $\varphi = 0°$. These energy values are too low, since repeated measurements of the spectra, averaged over all angles,[1,2] yield $E_{max} \approx 0.8$ MeV and $\bar{E} \approx 1.8$ MeV. In addition, the experimental data show that E_{max} and $\bar{E}$ increase appreciably with increasing angle.

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