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ON THE MECHANISM OF EMISSION OF PROMPT FISSION NEUTRONS

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The spectra of fission neutrons emitted at certain angles to the direction of flight of the fragments (0 and 180°, 40 and 120°, and 90°) have been measured. The spectra of neutrons emitted by light and heavy fragments separately are compared. The kinetic energy and temperature of the light and heavy U^{235} fission fragment groups at the instant of emission of fission fragments are also determined.

MODERN theory of nuclear fission presupposes that the fission neutrons are emitted from the excited moving fragments. Experiments on the investigation of the spectra of the fission neutrons confirm this assumption, but do not provide unequivocal data on the kinetic energy and temperature of the fission fragments at the instant when the neutrons are emitted. The purpose of the present investigation was to determine experimentally the kinetic energy and the temperature of the fragments.

MEASUREMENT PROCEDURE

The neutron energy was determined by measuring the time of flight. We measured the time interval between the instant of fission of the U^{235} nucleus in a scintillation fission chamber and the instant when the emitted neutrons were registered by a detector installed at a known distance L from the fission chamber. The neutron spectrum was measured with a 64-channel time analyzer.[1] The time stretching principle was used to measure short time intervals (0 to 0.25 μsec). FÉU-1V photomultipliers were used. The geometry of the experiment and a block diagram of the neutron spectrometer are shown in Fig. 1.

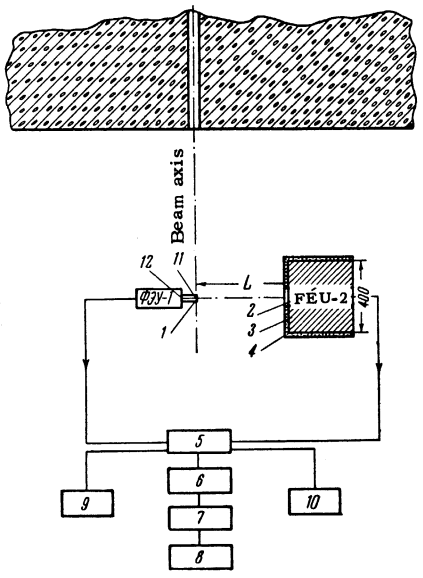

FIG. 1. Geometry of the experiment and block diagram of the spectrometer. 1 – fission chamber, 2 – neutron detector, 3 – lead, 4 – boron carbide, 5 – coincidence circuit, 6 – amplifier, 7 – pulse amplitude-to-duration converter, 8 – 64-channel time analyzer, 9 – fragment monitor, 10 – neutron monitor, 11 – layer of U^{235}, 12 – layer of ZnS(Ag).

The scintillation fission chamber was a 20 × 30 mm aluminum cup covered with a light pipe of

organic glass. One milligram of U^{235} was deposited on the bottom. A layer of ZnS(Ag) was placed on the light pipe to register the fission fragments emitted from the U^{235} layer. The U^{235} and ZnS(Ag) layers of 8 mm diameter were 20 mm apart. The chamber thus registered only fragments whose trajectories made angles not greater than 15° with the chamber axis. The chamber was connected to the vacuum system to produce the necessary gas pressure. The use of a ZnS(Ag) detector was made possible by the fact that only a small part of the leading edge of the pulse was used.

The variation of the spectrometer efficiency with the neutron energy was established experimentally. This was done with a scintillation fission chamber that registered almost all the fragments moving in a solid angle 2π. In this case the measured neutron spectrum corresponds to the general spectrum, which is well known from other investigations and obeys the Watt formula[2]

$$N(E) = e^{-E}\sinh\sqrt{2E}$$

(E is in megavolts).

To produce fission of the U^{235}, the chambers were bombarded with a beam of neutrons from a reactor, at an intensity of 1×10^9 neut/cm^{2}sec.

The fission neutrons were registered with a 30 × 20 mm stilbene crystal. The spectra of neutrons emitted at 0 and 180°, 40 and 120°, and 90° to the fragment flight direction were measured. The spectra of the neutrons traveling at 0 and 180° were measured at flight distances L equal to 25 and 40 cm. The spectra of the neutrons traveling at 40 and 120° were measured at L = 25 cm. During the measurement of the spectra, the fission chamber was evacuated to a pressure of 0.01 mm Hg. The spectrometer had an adjustment by which the time of flight could be measured in a range from 0 to 0.13 μsec.

In measurements of the spectra of the neutrons that travelled in the same direction as the fragments, a 50 × 45 mm liquid detector comprising a 2-percent solution of terphenyl in toluol was used for the light and heavy fragments separately. The flight distance L in these experiments was 50 cm. The spectrometer had an adjustment for measuring the time of flight in the range from 0 to 0.25 μsec. The different spectra were measured in the following manner.

The overall spectrum of both the heavy and light fragments was measured first with the fission chamber evacuated to 0.01 mm Hg. This was followed by measurement of the spectrum of the neutrons traveling in the same direction as the heavy

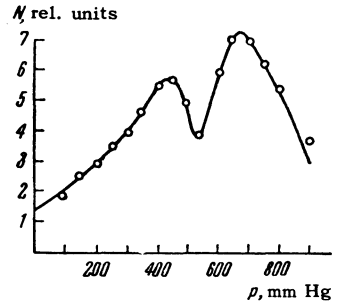

FIG. 2. Differential curve of the count of fragments in the fission chamber vs. the argon pressure.

fragments. The fission chamber was filled for this purpose with argon at 600 mm Hg. The heavy fragments were slowed down more rapidly in the gas, so that at this pressure the chamber recorded only the light fragments. This is seen from the differential fragment-count vs. chamber pressure curve of Fig. 2, where the maximum at p = 430 mm Hg corresponds to the heavy group of fragments, while that at 700 mm corresponds to the light group. From the geometry of the experiment it is seen that only neutrons traveling in the direction of the heavy fragments were registered in our case. Check calculations have shown that the spectrum of these neutrons is due essentially to the neutrons emitted from the heavy fragments. The spectrum of the neutrons from the light fragments was found by subtracting the heavy-fragment spectrum from the overall neutron spectrum.

To check the correctness of the experiments, control measurements were made, in which a paraffin scatterer 14 cm thick was placed between the fission chamber and the neutron detector. Such a paraffin layer scatters the neutrons almost completely and only the fission gammas reach the detector. If the experiments are correctly set up, then only the peak due to the gammas emitted during the instant of fission of the U^{235} remains on the curve. The results of the control measurements (see Fig. 5) confirm the correctness of the data obtained.

In reducing the measurement data, the position of the peak due to the fission gammas was taken as the time reference. The width of the gamma peak at half its height was used to determine the resolution of the spectrometer, which was found to be 5×10^{-9} sec.

EXPERIMENTAL RESULTS AND DATA REDUCTION

The experimentally obtained neutron spectra for different emission angles φ relative to the fragment trajectories are shown in Fig. 3. Reduction of these data yielded the neutron energy spectra in the laboratory frame (l.s.), shown in Fig. 4. It is seen from the curves that the number of neutrons

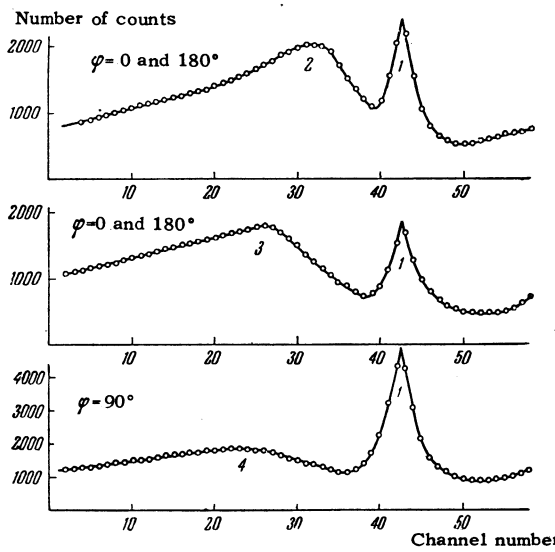

FIG. 3. Experimental spectra of fission neutrons for different angles of emission φ relative to the direction of fragment travel. 1 – peak of prompt fission gammas, 2 – spectrum for flight distance L = 25 cm, 3 – spectrum for L = 40 cm, and 4 – for 25 cm. The abscissas indicate the number of the time-analyzer channel.

and their energy distribution depend on the angle between the directions of the fragments of the neutrons. This result confirms the assumption that the fission neutrons are emitted by rapidly moving excited fragments. The ratio of the number of neutrons traveling at 90° to the fragments to the number of neutrons traveling in the same direction as the fragments, obtained experimentally by measuring the fission neutron spectra at different angles, was found to be 0.17. This quantity agrees well with the results of Wilson,[3] N(90°)/N(0°) = 0.18, and is somewhat smaller than the value obtained by Fraser,[4] 0.23.

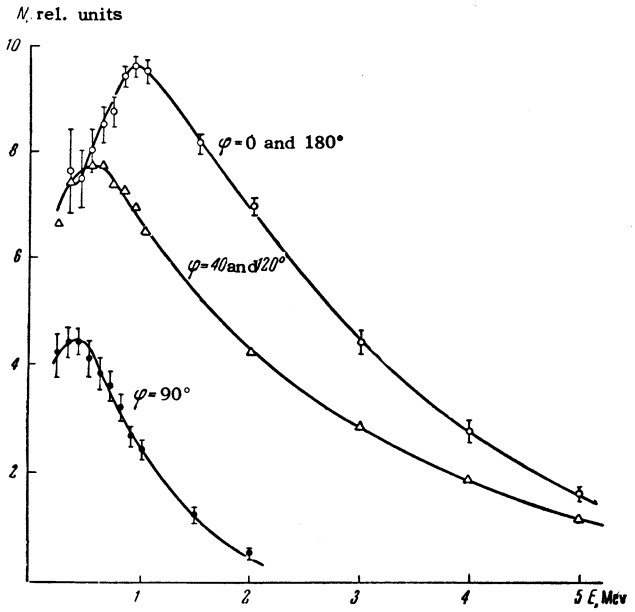

FIG. 4. Energy spectra of fission neutrons, lab. system.

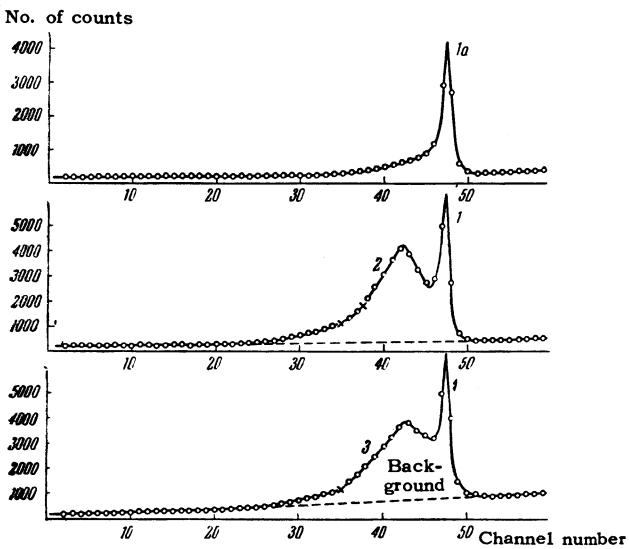

FIG. 5. Experimental curves, obtained in a liquid neutron detector. 1 – peak of prompt fission gammas, 1a – curve obtained with paraffin scatterer, 2 – summary curve for neutrons from light and heavy fragments for 0 and 180°, 3 – spectrum of neutrons traveling in the direction of the heavy fragments.

The experimental curves for the separate measurements of the spectra of the neutrons from the light and the heavy groups of fragments are shown in Fig. 5. The corresponding energy spectra of the neutrons are shown in Fig. 6. The maxima in the 0.2 – 0.3 Mev region on the curves are obviously produced by neutrons traveling in a direction opposite to the fragments that emit them at speeds smaller than the fragment speeds. The main part of the spectra is made up, on the other hand, by neutrons traveling in the same direction as the fragments. The neutron spectra are thus the sums of these two components. An analysis of the curves of Figs. 5 and 6 permits a determination of the fragment velocity at the instant when it emits the neutrons. The kinks and the experimental curves of Fig. 5, denoted by crosses and corresponding to the minima on the curves of Fig. 6, pertain to neutrons with zero energy in the reference frame of the resting fragments. In the laboratory system, consequently, these neutrons have the same velocities as the fragments from which they are emitted. The velocities of the heavy and light fragments obtained by such an analysis are:

$$V_h = (0.88 \pm 0.08) \cdot 10^9 \text{ cm/sec},$$
$$V_l = (1.1 \pm 0.12) \cdot 10^9 \text{ cm/sec}.$$

The values obtained for the fragments at the instant of neutron emission are close to values obtained by others, $V_h = 0.96 \times 10^9$ cm/sec and $V_l = 1.42 \times 10^9$ cm/sec.[5]

To determine the fragment excitation energy it is necessary to recalculate the obtained spectra

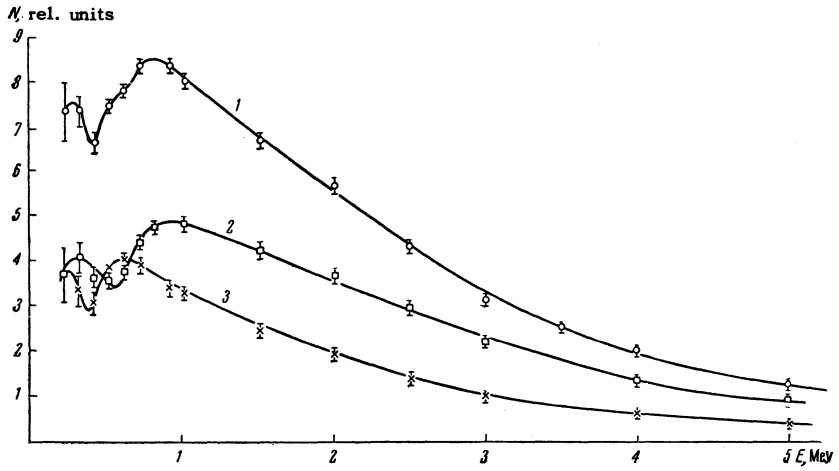

FIG. 6. Neutron spectra for the light and heavy groups of fragments, l.s. 1 – summary spectrum of neutrons from heavy and light fragments, for $\varphi = 0$ and 180°, 2 – spectrum of neutrons traveling in the direction of the light fragments, 3 – spectrum of neutrons traveling in the direction of the heavy fragments.

from the laboratory system to that of the fragments at rest. The neutron energy E in the laboratory system can be calculated from the formula[6]

$$E(\varepsilon, \varphi) = \varepsilon [1 - r^2 + 2r^2\cos^2\varphi + 2r\cos\varphi(1 - r^2 + r^2\cos^2\varphi)^{1/2}], \quad (1)$$

where φ is the angle between the fragment and neutron flight directions, r is the ratio of the fragment speed to the neutron speed in the rest frame of the fragment, and ϵ is the energy of the neutron in the same frame. The probability per unit solid angle of emission of a neutron at an angle φ is given by

$$f(\varepsilon, \varphi) = \frac{1}{4\pi}\left(\frac{E}{\varepsilon}\right)^{3/2}\left\{1 + r\left[1 - \frac{E}{\varepsilon}\sin^2\varphi\right]^{1/2}\right\}^{-1}. \quad (2)$$

The l.s. neutron spectrum at an emission angle φ can therefore be described by

$$N(E, \varphi) = f(\varepsilon, \varphi)\, N(\varepsilon), \quad (3)$$

where $N(\epsilon)$ is the neutron spectrum in the rest frame of the fragment.

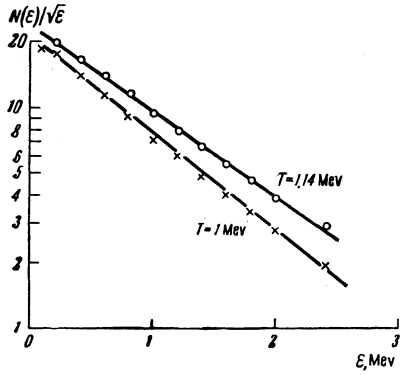

FIG. 7. Neutron spectra for the light (circles) and heavy (crosses) groups of fragments in a system where the fragments are at rest. Solid curves – calculated from Eq. (4).

Using this formula, the experimental spectra obtained in this investigation can be recalculated to the rest frame of the fragments. Figure 7 shows the neutron spectra separate for the light and for the heavy group of fragments (in the frame where these fragments are at rest), obtained by recalculating the experimental curves of Fig. 6. An analysis of the spectra has shown that they fit quite well the Maxwellian distribution

$$N(\varepsilon) \sim \sqrt{\varepsilon}\exp(-\varepsilon/kT), \quad (4)$$

where T is the neutron temperature of the fragments. The experimental spectra agree best with the theoretical ones, calculated from (4), when the fragment temperatures are T_l = 1.14 Mev and T_h = 1 Mev. In addition, analysis has shown that the light fragments emit 30 percent more fragments than the heavy ones. A similar result was obtained by Fraser.[4]

It must be noted in conclusion that the procedure employed here can be successfully applied to an investigation of the neutron-fission spectra of other elements, including the neutrons from the spontaneous fission of Cf^{252}.

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