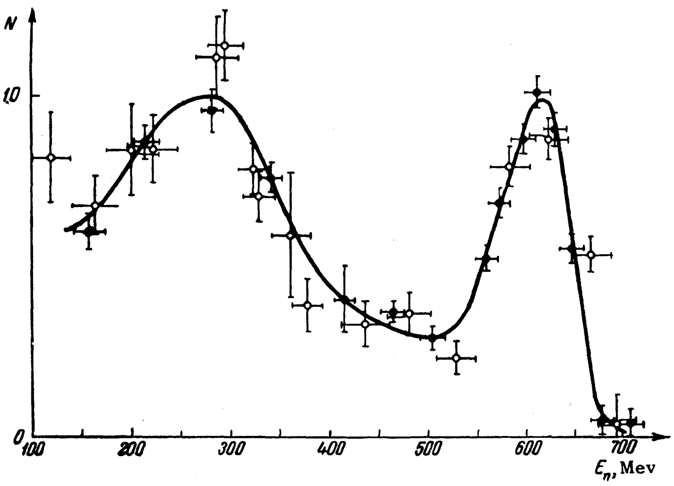


FIG. 2. Neutron energy spectrum. The black dots refer to the data of the present measurements. The circles refer to the data of reference 1 with the corrections indicated in the text.

has not been determined experimentally because of the great difficulty involved.

The present measurements, which were made with a high-resolution detector and in which there was no pion contamination, indicate that the maximum at 610-Mev has a smaller half-width (approximately 100-Mev) than that given in reference 1.

The origin of the two maxima in the neutron spectrum has been discussed in reference 1, to which the reader is referred.

In conclusion the authors wish to thank V. P. Zrelov for a number of valuable comments in connection with the present work.

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## *RELATIVE YIELDS OF DELAYED NEUTRONS IN FISSION OF* $U^{238}$, $U^{235}$ *AND* $Th^{232}$ *BY FAST NEUTRONS*

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MEASUREMENTS have been made of the relative yields of delayed neutrons in fission of natural uranium, $U^{235}$ (90% enriched) and $Th^{232}$ by neutrons with energies of $15.0 \pm 0.9$, $3.3 \pm 0.7$, and $2.4 \pm 0.3$ Mev.

The 15.0-Mev neutrons were obtained from a thick tritium target which was bombarded by 440-kev deuterons. The 3.3 and 2.4-Mev neutrons were obtained from the $D(d, n)He^3$ reaction. A target of heavy ice was bombarded by 920-kev deuterons.

The thermal neutrons were also recorded. The latter were obtained by slowing down fast neutrons from the $Be^9(d, n)B^{10}$ reaction in a paraffin block which surrounded the target. The number of delayed neutrons for a sample enclosed in cadmium was less than 5% of the number of the delayed neutrons without the cadmium.

In order to determine the effect of target thickness on the delayed-neutron yield ratio measurements were made using $U^{235}$ samples of different thickness in fission by 15.0-Mev neutrons. The $U^{238}$, $Th^{232}$ and $U^{235}$ samples were 35 mm in diameter and 9, 10, and 8 mm thick respectively.

The detector was a bank of four $BF_3$ counters connected in parallel and surrounded by paraffin.

The samples of fissile material were irradiated by the fast-neutron flux for a given time interval and then dropped into the counter block, located at a distance of approximately 1.5 meters below the target. When the sample was located the ion source of the accelerator and the high voltage power supply were switched off. The time required to move the sample was 0.20 to 0.30 sec.

The neutron detection circuit was switched on when the sample reached the center of the counter. The pulses from the counter bank were amplified and then recorded in a time analyzer. The channels in the time analyzer record in sequence the time required for a predetermined number of pulses.

Two series of exposures were made, 300 and 30 sec. The corresponding measurement times were 360 and 270 sec. There was essentially no background during the measurements; the background was checked by using a steel sample in place of the fissile material.

| Group Number | Decay time | Relative yield | Group Number | Decay time | Relative yield |
|---|---|---|---|---|---|
| | $U^{235}$ Thermal | | | $U^{238}$(2.4 Mev) | |
| 1 | 55.55 | 0.039 | 1 | 54.88 | 0.012 |
| 2 | 22.02 | 0.245 | 2 | 21.41 | 0.152 |
| 3 | 6.06 | 0.206 | 3 | 5.47 | 0.176 |
| 4 | 2.25 | 0.418 | 4 | 1.95 | 0.440 |
| 5 | 0.462 | 0.092 | 5 | 0.568 | 0.220 |
| | $U^{235}$(2.4 Mev) | | | $U^{238}$(3.3 Mev) | |
| 1 | 56.09 | 0.037 | 1 | 53.51 | 0.014 |
| 2 | 22.27 | 0.221 | 2 | 20.34 | 0.153 |
| 3 | 5.46 | 0.217 | 3 | 5.66 | 0.169 |
| 4 | 2.17 | 0.409 | 4 | 2.10 | 0.423 |
| 5 | 0.435 | 0.116 | 5 | 0.590 | 0.241 |
| | $U^{235}$(3.3 Mev) | | | $U^{238}$(15 Mev) | |
| 1 | 55.16 | 0.043 | 1 | 56.11 | 0.022 |
| 2 | 21.63 | 0.219 | 2 | 21.92 | 0.167 |
| 3 | 6.32 | 0.210 | 3 | 5.20 | 0.171 |
| 4 | 2.24 | 0.428 | 4 | 2.27 | 0.412 |
| 5 | 0.650 | 0.100 | 5 | 0.600 | 0.228 |
| | $U^{235}$(15 Mev; 8 mm) | | | $Th^{232}$(2.4 Mev) | |
| 1 | 54.70 | 0.052 | 1 | 53.32 | 0.038 |
| 2 | 20.93 | 0.182 | 2 | 19.63 | 0.127 |
| 3 | 6.27 | 0.206 | 3 | 6.37 | 0.195 |
| 4 | 2.27 | 0.396 | 4 | 2.08 | 0.408 |
| 5 | 0.646 | 0.164 | 5 | 0.651 | 0.232 |
| | $U^{235}$(15 Mev; 4 mm) | | | $Th^{232}$(3.3 Mev) | |
| 1 | 53.98 | 0.058 | 1 | 54.97 | 0.037 |
| 2 | 20.60 | 0.201 | 2 | 21.64 | 0.137 |
| 3 | 5.60 | 0.209 | 3 | 6.61 | 0.190 |
| 4 | 2.23 | 0.366 | 4 | 2.07 | 0.423 |
| 5 | 0.659 | 0.166 | 5 | 0.664 | 0.213 |
| | $U^{235}$(15 Mev; 2.3 mm) | | | $Th^{232}$(15 Mev) | |
| 1 | 55.15 | 0.051 | 1 | 53.80 | 0.044 |
| 2 | 22.32 | 0.181 | 2 | 19.07 | 0.154 |
| 3 | 6.29 | 0.203 | 3 | 6.42 | 0.169 |
| 4 | 2.17 | 0.402 | 4 | 2.15 | 0.428 |
| 5 | 0.638 | 0.163 | 5 | 0.553 | 0.205 |

The decay curves for a given element and the corresponding energy obtained in different experiments were combined. In combining these results use was made of the fact that the ratio of the counting rates at any instant of time for the decay curves obtained with different irradiation intensities is equal to the ratio of the total counts (i.e., the total number of pulses) for the same curves over equal time intervals (in the present case these intervals are 360 and 270 sec for exposures of 300 and 30 sec). Five groups of delayed neutrons were resolved. The relative yields of 55- and 22-sec decays were determined from the decay curves obtained using the 300-sec exposure. These two groups were resolved using a method of successive approximations. The three later groups (with shorter periods) were determined from the decay curve obtained with the 30-sec exposure. A sixth decay time could not be resolved because of its low intensity and short lifetime.

The contribution of the first and second delayed-neutron groups in short exposures was determined for each individual decay curve appearing in the total from the integrated pulse count over a time interval of approximately 60 sec (when the contribution of the short-lived decays was negligibly small) to 270 sec (end of count), using the intensity ratio for the first two groups as obtained from an analysis of the curves for the 300-sec exposures. In computing the contributions of the first two groups we used the mean value of the initial counting rate in the individual measurements carried out at the same exposure intensities.

All curves were computed by a least-squares method. The results are shown in the table.

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## *RADIATION OF A MULTILEVEL SYSTEM MOVING IN A MEDIUM WITH A VELOCITY GREATER THAN THE VELOCITY OF LIGHT*

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THE formula for the complex ("superlight") Doppler effect, in which the radiator moves with a velocity $v > c/n$ in a transparent medium characterized by a refractive index $n(\omega)$, is of the form[1]

$$\omega(\theta) = \omega_{ik}\sqrt{1-\beta^2}/|1-\beta n(\omega)\cos\theta|, \qquad (1)$$

where $\omega_{ik}$ is the frequency in the system in which the radiator is at rest, $\beta = v/c$, and $\theta$ is the angle between $\mathbf{v}$ and the wave normal. In a quantum-mechanical analysis Eq. (1) is obtained (cf. reference 2) from the laws of conservation of energy and momentum where the energy and momentum of the photon in the medium are respectively $\hbar\omega$ and $\hbar\omega n/c$. In the quantum-theory formulation, the Cerenkov condition $\beta n \cos\theta_0 = 1$ is obtained in a similar way (cf. reference 3). In the normal Doppler effect [when $\beta n(\omega)\cos\theta < 1$] the radiating system makes a transition from an upper state with energy $\epsilon_i$ to a lower state with energy $\epsilon_k = \epsilon_i - \hbar\omega_{ik}$. In the complex Doppler effect, however, [when $\beta n(\omega)\cos\theta > 1$, i.e., inside the Cerenkov cone] the radiation is characterized by transitions of the system in the upward direction — from a level $\epsilon_k$ to a level $\epsilon_i = \epsilon_k + \hbar\omega_{ik}$.[2] As a result, even in the absence of any other interaction, the system does not radiate and the probability of its remaining at the levels $\epsilon_i$ and $\epsilon_k$ is determined by the total probability of radiation at the normal and complex Doppler frequencies. Two points must be kept in mind in considering the possibility of observing the complex Doppler effect. First, if the radiator does not move in the medium itself but in an empty channel or in a slit of width smaller than the wave length of the radiated waves the characteristic features of the "superlight" radiation still obtain.[4,5] The complex Doppler effect can be important in motion of electrons in a magneto-active plasma when the losses are small; this case is of special interest in practice (cf. below). It is the purpose of the present note to point out the interesting possibilities associated with the faster-than-light motion of a multilevel system. If the system is initially at one level, say the ground state, in the course of time it may be found in all states to which it can make a transition as a result of direct or multiple radiative transitions (transitions upward with the radiation of frequency $\omega$ are possible only if the relation in (1) obtains with $\beta n(\omega)\cos\theta > 1$). The level populations are determined by the equations:

$$dN_i/dt = -\sum_k A_{ik}N_i + \sum_k B_{ik}N_k,$$

where $A_{ik}$ is the probability for a radiative transition from level i to level k while $B_{ik}$ is the probability for transition from level k to level i (this scheme, similar to that used to describe radioactive decay, can be obtained from the quantum theory of radiation, using certain justifiable assumptions[6]). In the dipole transitions between any states, i and k, the radiation intensity at the normal and complex Doppler frequencies can be determined from the classical formulas[1,2] by replacing the square of the amplitude of the dipole moment by $4|\mathbf{p}_{ik}|^2$. For example, with $n = \text{const}$ and a moment $\mathbf{p}_{ik}$ oriented along the velocity vector $\mathbf{v}$, the energy radiated per unit time into unit solid angle is

$$W(\theta) = \omega_{ik}^4(1-\beta^2)^3|\mathbf{p}_{ik}|^2\sin^2\theta/2\pi c^3|1-\beta n\cos\theta|^5, \qquad (2)$$

where the angle $\theta$ is related to $\omega$ by Eq. (1) and $\mathbf{p}_{ik}$ is the matrix element for the rest system.

When $\beta n\cos\theta \to 1$, it is obviously impossible to neglect dispersion. In a number of cases, however, a reasonable approximation can be obtained by taking n as a step function: $n(\omega) = n$ for $\omega < \omega_c$ and $n = 1$ for $\omega > \omega_c$. This behavior for the refractive index n is reasonable in the case of weak dispersion for motion in a channel or in a slit as well as for an extended radiating system (in this case when $\cos\theta_0 \sim 1$ the frequency $\omega_c \sim 2\pi v/l$ where $l$ is the radius of the channel, the width of the slit or a typical dimension of the system). If the angle $\theta_c$ is close to the Cerenkov angle $\theta_0$, it is clear from Eq. (2) that the intensity