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.

[1] B. Watt, Phys. Rev. **87**, 1037 (1952).

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

[3] R. Leachman, Paper at the International Conference on the Peaceful Uses of Atomic Energy, Geneva (1955).

[4] Kovalev, Andreev, Nikolaev, and Guseinov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1069 (1957), Soviet Phys. JETP **6**, 825 (1958).

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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 Fraser[14] for the fission U^{235} by thermal neutrons, was extended to include the entire nucleus under consideration. The calculated values of E_n were found to be in good agreement with measured values of $d\nu/dE_x = 1/E_n$ (Refs. 15 — 17).

The mean energy E_γ of the instantaneous γ rays was assumed constant, 8 Mev, in the calculations, as confirmed by experiments on the study of the prompt-fission γ rays from U^{235}(n, f) and Cf^{252} (Refs. 15, 18).

For comparison with the calculations, all the experimental values of γ, for the fission induced by neutrons, were reduced to values of ν for spontaneous fission of the corresponding compound nuclei, using the formula $d\nu/dE_x = 1/E_n$. The validity of this operation was confirmed by direct comparison of ν for the processes Pu^{235}(n, f) and Pu^{241}(n, f) (Ref. 5) with ν for spontaneous fission of Pu^{240} and Pu^{242} (Refs. 1 — 3).

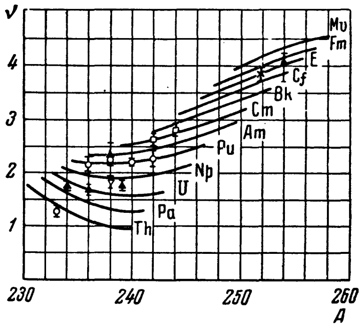

Fig. 1. Dependence of the average number of prompt fission neutrons on A, for various Z. Lower point ○ – Th, ▲ – U, ▽ – Np, ○ – Pu, □ – Cn, × – Cf, ● – Fm.

The diagram shows a family of curves of ν as functions of A for various Z. Most experimental data are in satisfactory agreement with the calculations. An exception is the value of ν for the spontaneous fission of U^{238} (Ref. 7). The value of ν for the spontaneous fission of Th^{232} was not compared with the results of these calculations, for, according to the latest measurements for the period of spontaneous fission of Th^{232} (Ref. 19), there is a certain doubt concerning the value $\nu_{Th}/\nu_U = 1.07 \pm 0.1$ (Ref. 6).

The non-monotonic course of $\nu(A)$ is due to the shell structure of the fragments. Without taking the shells into account, $d\nu/dA > 0$. On nuclei with $A < 240$, i.e., with $A_\ell < 100$, the nearness of a shell with 50 neutrons manifests itself — the excitation energy increases with diminishing A, and the sign of $d\nu/dA$ is reversed.

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[1] Crane, Higgins, and Bowman, Phys. Rev. **101**, 1804 (1956).
[2] Diven, Martin, Taschek, and Terrell, Phys. Rev. **101**, 1012 (1956).
[3] Hicks, Ise, and Pyle, Phys. Rev. **101**, 1016 (1956).
[4] Kuz'minov, Kutsaeva, and Bondarenko, Атомная энергия (Atomic Energy) **4**, No. 2 (1958).
[5] D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, Suppl. 1957.
[6] Barclay, Galbraith, and Whitehouse, Proc. Phys. Soc. **A65**, 73 (1952).
[7] D. J. Littler, Proc. Phys. Soc. **A65**, 203 (1952).
[8] Choppin, Harvey, Hicks, Ise, and Pyle, Phys. Rev. **102**, 766 (1956).
[9] A. E. S. Green, Phys. Rev. **95**, 1006 (1954).
[10] P. Fong, Phys. Rev. **102**, 434 (1956).
[11] W. J. Swiatecki, Phys. Rev. **100**, 936 (1955).
[12] Kovalev, Andreev, Niklaev, and Guseinov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1069 (1957), Soviet Phys. JETP **6**, 825, (1958).
[13] Hjalmar, Slatis, and Tompson, Ark. Fyzik. **10**, 357 (1956).
[14] J. S. Fraser, Phys. Rev. **88**, 536 (1952).
[15] R. B. Leachman, Phys. Rev. **101**, 1005 (1956).
[16] Smirenkin, Bondarenko, Kutsaeva, Mishchenko, Prokhorova, and Shemetenko, Атомная энергия (Atomic Energy) **4**, No. 2 (1958).
[17] Kalashnikova, Lebedev, and Spivak, Атомная энергия (Atomic Energy) **2**, 18 (1957).
[18] Smith, Fields, and Friedman, Phys. Rev. **104**, 699 (1956).
[19] Podgurskaia, Kalashnikova, Stoliarov, Vorob'ev, and Flerov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 503 (1955), Soviet Phys. JETP **1**, 392 (1955).

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ON THE DOUBLE BETA-DECAY OF Ca^{48}

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A number of experimental researches have shown[1,2] that the period of double β-decay is greater than 10^{18} years. In this connection, the necessity has arisen of re-examining the esti-