CORRELATION BETWEEN THE MEAN NUMBER AND MEAN ENERGY OF PROMPT FISSION NEUTRONS AND THE PROPERTIES OF THE FISSIONING NUCLEUS

V. P. KOVALEV and V. S. STAVINSKII

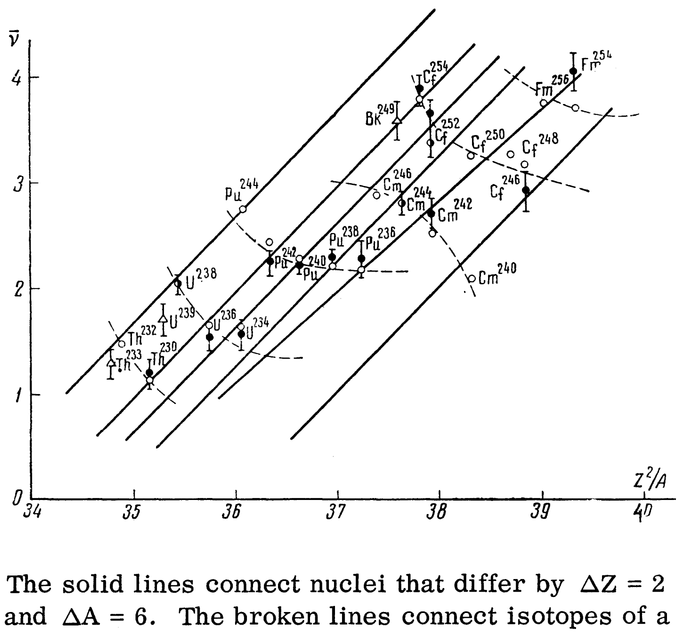
Submitted to JETP editor May 17, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1304-1306 (October, 1961)

Experimental data on the mean number $\bar{\nu}$ and mean energy $\bar{E}$ of prompt fission neutrons are considered. A correlation is established between $\bar{\nu}$ and the spontaneous fission periods of even-even isotopes. It is noted that $\bar{E}$ has a tendency to split up, depending on the parity of the nucleons of the fissioning nucleus. An analysis reveals that the properties of the fissioning nucleus that are related to the parity of the nucleons influence the fission process at all its stages up to disintegration.

A study of the systematics of spontaneous fission periods T_f and fission thresholds E_f [1] reveals that the properties of the original nucleus which are associated with the parity of the nucleons influence the fission process up to the saddle-point stage. Experimental data on the mean number and the mean energy of the prompt fission neutrons permits one to confirm the influence of these properties on the fission process and on later stages right up to disintegration.

The following graph presents the experimental dependence of $\bar{\nu}$ on Z^2/A (black dots). The data were taken from the work of Bondarenko et al. [2]



The solid lines connect nuclei that differ by $\Delta Z = 2$ and $\Delta A = 6$. The broken lines connect isotopes of a given element. The plotted values of $\bar{\nu}$ fall near the intersections of these lines. The graph of $\log T_f$ vs. Z^2/A [3] forms a similar grid. Thus, for even-even nuclei there is a distinct correlation between $\bar{\nu}$ and $\log T_f$.

Since there is a comparatively simple semi-empirical formula [1] for $\log T_f$, it is natural for one to attempt to establish a similar formula for $\bar{\nu}$. An analysis of the experimental data on even-even nuclei led to the following semi-empirical formula for $\bar{\nu}$:

$$\bar{\nu} = 0.7Z^2/A - 23.3 + 0.55\,(0.9 + 0.38Z - Z^2/A)\,\delta M. \quad (1)$$

Here δM is the difference between the ground-state mass M of the fissioning nucleus and the mass as computed by the semi-empirical Green formula.

In formula (1) the first two terms correspond to a straight line passing through maximum stability with respect to spontaneous fission, while the third term accounts for the correlation with the mass of the fissioning nucleus. The values computed by formula (1) are shown in the graph (the light circles). The experimental values of M used in the computation were taken from Glass et al. [4]

The systematics of $\bar{\nu}$ has been studied earlier. [2,5] Crane et al. [5] have noted that $\bar{\nu}$ has a general tendency to increase with the mass number of the fissioning nucleus. Bondarenko et al. [2] have attempted a more detailed systematization. An energy balance equation was used to compute $\bar{\nu}$. The computed values of $\bar{\nu}$ for U^{238} and Pu^{238} are in poor agreement with the experimental data. This may be due to the fact that in their investigation the authors disregarded the effect of the correlation between the kinetic energy of the fragments and δM, which must occur, especially if it is assumed, as they have, that E_γ = const.

The satisfactory agreement between formula (1) and the experimental data permits $\bar{\nu}$ to be estimated for those even-even isotopes for which the experimental data are either lacking or unreliable. Specifically, for Th^{232} formula (1) gives $\bar{\nu} = 1.54$, which, together with the observed $\bar{\nu}$ for U^{238}, correlates very well with the spontaneous fission periods of these nuclei.

The aggregate of experimental values for $\bar{E}$ [6-10] makes it possible to advance the theory that the mean energy of the fission neutrons depends on the parity of the nucleons in the fissioning nucleus. If the Z^2/A dependence of the hardness parameter, $B = 2\bar{E}/3$, of the fission neutron spectra is plotted, then it can be seen that this parameter is an increasing function of Z^2/A, as has been noted earlier.[11] The one difference which is observed is that the values of B for isotopes with odd A run somewhat higher ($\Delta B \approx 0.1$) than for even isotopes, i.e., a splitting appears in $\bar{E}$ between isotopes with even and odd A. This split in the value of $\bar{E}$ which depends on the parity of A explains the difference between the computed and experimental data for U^{239}.[9,11]

A direct relation between $\bar{E}$ and $\bar{\nu}$ was discovered by Terrel (see Leachman[7]) in an analysis of even-even isotopes and is of the form

$$\bar{E} = 0.78 + 0.62\sqrt{\bar{\nu} + 1}. \quad (2)$$

It is not difficult to see that formula (2) is not in agreement with the experimental data for the odd isotopes Th^{233} and U^{239}.[8,9] Formula (2) was based on the assumption that temperature T of the fragments is related to their excitation energy E_{ex} by the relationship $T \sim \sqrt{E_{ex}}$. If the function $\bar{E}(Z^2/A)$ is known, then formula (2) can be used to relate $\bar{\nu}$ to Z^2/A for even-even isotopes. The expression thus obtained for $\bar{\nu}$ fails to agree even qualitatively with the form of formula (1). If it is assumed that T depends only slightly on E_{ex}, then for the even-even isotopes we find

$$\bar{E} = 0.78 + 2\,(0.41 + 0.067\bar{\nu}). \quad (3)$$

The formula for $\bar{\nu}$ obtained by using Eq. (3) is analogous in form to formula (1). If the kinetic energy of an incident neutron is changed from thermal to ~ 14 Mev, then $\bar{\nu}$ is approximately doubled. According to the equation $T \sim \sqrt{E_{ex}}$, this corresponds to a temperature change of 40 – 50%. Equation (3) means a change in T of ~ 20% which is in better agreement with the conclusion derived from an analysis of the spectra of inelastically scattered neutrons,[12] that the nuclear temperature depends only slightly on the excitation energy.

The authors wish to express their gratitude to Professor I. I. Bondarenko for a discussion of this paper.

[1] W. J. Swiatecki, Phys. Rev. **100**, 937 (1955); Phys. Rev. **101**, 97 (1956).

[2] Bondarenko, Kuz'minov, Kutsaeva, Prokhorova, and Smirenkin, Second International Conference on the Peaceful Uses of Atomic Energy, Paper No. 2187 (Geneva, 1958).

[3] A. Ghiorso, First International Conference on the Peaceful Uses of Atomic Energy, Vol. 8, Paper No. 718 (Geneva, 1955).

[4] Glass, Thompson, and Seaborg, J. Inorg. Nucl. Chem. **1**, 3 (1955).

[5] Crane, Higgins, and Bowman, Phys. Rev. **101**, 1804 (1955).

[6] Smith, Fields, Friedman, Cox, and Sjoblum, Second International Conference on the Peaceful Uses of Atomic Energy, Paper No. 690 (Geneva, 1958).

[7] R. Leachman, ibid, Paper No. 2467.

[8] Zamyatnin, Safina, Gutnikova, and Ivanova, Atom. Energiya (Atomic Energy) **4**, 337 (1958); transl. in Soviet Journal of Atomic Energy **4**, 443 (1958).

[9] Vasil'ev, Zamyatnin, Il'in, Sirotinin, Toropov, and Fomushkin, JETP **38**, 671 (1960), Soviet Phys. JETP **11**, 483 (1960).

[10] V. I. Kalashnikova, Dissertation, Inst. Atom. Energy, Acad. Sci. (1959).

[11] V. P. Kovalev and V. S. Stavinskii, Atomn. Energiya **5**, 649 (1958); Transl. in Soviet Journal of Atomic Energy **5**, 1588 (1958).

[12] V. S. Stavinskii, Dissertation, Moscow Eng. Phys. Inst. (1959).

Translated by A. Skumanich
222