[9]The very small nuclear recoil energies after the β decay, electron capture, or γ emission are not expected to produce a change in the lattice location of the decay products. It has been shown for the case of ^{212}Bi in silicon that β decay does not produce a change in the lattice location. [E. Uggerhoj, in *Radiation Damage in Reactor Materials* (International Atomic Energy Agency, Vienna, 1969), Vol. 1.]

[10]A. J. Freeman and R. E. Watson, Phys. Rev. 123, 2027 (1961).

[11]E. Daniel and J. Friedel, J. Phys. Chem. Solids 24, 1601 (1963).

[12]D. A. Shirley and G. A. Westenbarger, Phys. Rev. 138, A170 (1965).

[13]A. E. Balabanov and N. N. Delyagin, Zh. Eksp. Teor. Fiz. 54, 1402 (1968) [Sov. Phys. JETP 27, 752 (1968)].

[14]I. A. Campbell, Proc. Roy. Soc., Ser. A 311, 131 (1969).

[15]D. A. Shirley, Phys. Lett. 25A, 129 (1967).

[16]M. B. Stearns, Scientific Research Staff Publication Preprint, Ford Motor Company, 28 January 1971 (to be published), and Phys. Lett. 34A, 146 (1971).

Measurement of the Variance of the Number of Neutrons Emitted in Fission of ^{252}Cf as a Function of the Fragment Mass and Total Kinetic Energy

Avigdor Gavron

Israel Atomic Energy Commission, Soreq Nuclear Research Center, Yavne, Israel, and Weizmann Institute of Science, Rehovot, Israel

and

Zeev Fraenkel

Weizmann Institute of Science, Rehovot, Israel

(Received 17 August 1971)

We have measured the variance of the number of neutrons emitted by individual fragments in fission of ^{252}Cf as a function of the fragment mass and the total kinetic energy released. The variance does *not* show pronounced "sawtooth" structure as a function of the fragment mass. We deduce from this that the correlation coefficient between the excitation energies of complementary fission fragments is substantially less than unity for at least some portions of the fragment mass-ratio distribution.

The distribution of the average number of neutrons emitted in fission by the individual fission fragments provides a way of estimating the partition of the total excitation energy between the two fragments. A summary of the data on this distribution has been presented by Terrel.[1] From these data it is evident that the sawtooth dependence of the average number of neutrons $\bar{\nu}(A)$ as a function of the fragment mass A is a general feature of low-energy fission. Data presented by Bowman *et al.*,[2] Milton and Fraser,[3] and Nardi and Fraenkel[4] show that the derivative of the average number of neutrons with respect to the total fragment kinetic energy E_K, denoted by $(\partial\bar{\nu}/\partial E_k)(A)$, also exhibits a sawtooth dependence as a function of the fragment mass. This parallel behavior of $\bar{\nu}(A)$ and $(\partial\bar{\nu}/\partial E_k)(A)$ indicates that fragments with high excitation energy are also more susceptible to receiving additional excitation energy. The results do not, however, provide any information about the *width* of the excitation-energy distribution or about any possible cross correlation between the excitation energies of the two fragments.

We have measured the variance in the neutron-number distribution of individual fission fragments emitted in ^{252}Cf fission, as a function of the fragment mass and total kinetic energy. A ^{252}Cf source of about 2×10^5 fission/min deposited on a thin Ni backing was placed between two surface-barrier fission fragment detectors, denoted F_1 and F_2 in Fig. 1. These detectors together with the source were placed inside an aluminum vacuum chamber of 30-cm diam and 0.5-cm wall thickness. The fission fragment detectors F_1 and F_2 were placed at a distance of 5.5 cm from the source and subtended an angle of 19° with respect to it. The neutrons were detected by means of

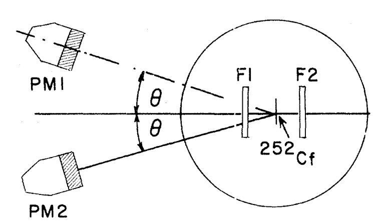

FIG. 1. Experimental arrangement.

the time-of-flight method with the aid of two identical NE102 plastic scintillators (manufactured by Nuclear Enterprises Ltd.), denoted PM_1 and PM_2 in Fig. 1, which faced the same fission detector. The two scintillators, each of 5-in. diam and 2-in. length, were situated outside the chamber at a distance of 27.5 cm between the source and the front of the scintillator. The angle θ between each of the scintillators and the source-fission detector axis was 22°30′ (see Fig. 1). The fission detector F_1 furnished the start pulse for the time-of-flight measurement, through a commercial time-pickoff unit. The time resolution of the time-of-flight system as determined by the width of the prompt γ peak was 1.6 nsec full width at half-maximum.

Three different types of events were collected by a four-dimensional analyzer and stored on magnetic tape: (1) double-coincidence events between the two fission fragment detectors F_1 and F_2; (2) triple-coincidence events between F_1, F_2, and one of the scintillators; and (3) fourfold-coincidence events between all four detectors. A total of 10^6 fourfold coincidence events were obtained over a period of 8 months. Of these, 2×10^5 events were produced by neutrons detected in both PM_1 and PM_2. The data were analyzed as follows: The double coincidence events were used to obtain the fission detector calibration constants using the method of Schmitt, Kiker, and Williams.[5] They were later used to obtain the fragment mass and kinetic energy for each event. Denoting by $N_0(A, E_K)$ the number of double-coincidence events for a given mass A and total kinetic energy E_K, by $N_1(A, E_K)$ the number of triple-coincidence events in which neutrons were detected in PM_1 or PM_2, by $N_2(A, E_K)$ the number of fourfold-coincidence events (neutrons detected in both PM_1 and PM_2), and by $\epsilon(A, E_K)$ the neutron detection efficiency averaged over the neutron velocity, the following relations hold:

$$\begin{aligned} N_1(A,E_K) &= 2\langle \nu(A,E_K)\epsilon(A,E_K)\rangle N_0(A,E_K), \\ N_2(A,E_K) &= \langle \nu(A,E_K)[\nu(A,E_K)-1]\epsilon^2(A,E_K)\rangle \\ &\quad \times N_0(A,E_K). \end{aligned} \tag{1}$$

(The angular brackets denote average over the neutron number distribution.)

These equations are based on the assumption that the neutrons detected in PM_1 and PM_2 are emitted from the fission fragment moving towards F_1. The factor of 2 in Eq. (1) is a result of the use of two neutron detectors, each of which has an equal probability of detecting a neutron.

In the following we assume that $\epsilon(A, E_K)$ is independent of $\nu(A, E_K)$. (The only possible dependence is through the dependence of the average center-of-mass kinetic energy of the neutrons on the number of neutrons emitted in a cascade. This is a very small effect which is corrected for below.) We obtain

$$\langle \nu(A,E_K)\epsilon(A,E_K)\rangle = \bar{\nu}(A,E_K)\bar{\epsilon}(A,E_K), \tag{3}$$

$$\begin{aligned} &\langle \nu(A,E_K)[\nu(A,E_K)-1]\epsilon^2(A,E_K)\rangle \\ &\quad = \langle \nu(A,E_K)[\nu(A,E_K)-1]\rangle\bar{\epsilon}^2(A,E_K). \end{aligned} \tag{4}$$

From these equations we obtain

$$\frac{\langle \nu(A,E_K)[\nu(A,E_K)-1]\rangle}{\bar{\nu}^2(A,E_K)} = \frac{4N_2(A,E_K)N_0(A,E_K)}{N_1^2(A,E_K)}. \tag{5}$$

The variance of the neutron number distribution can be calculated from Eq. (5). Values of $\bar{\nu}(A, E_K)$ used here were obtained from a threefold coincidence experiment which was analyzed by the method of Bowman *et al.*[2] The following second-order effects were corrected for in the calculation of the variance: (1) the probability of detecting neutrons from the opposite fission fragment; (2) the probability that some "single-neutron events" were produced by two or more neutrons hitting the same detector; and (3) the variation of the neutron center-of-mass kinetic energy with the number of neutrons emitted by the fragment.

We present here the main results of the experiment. Denoting by $\sigma_\nu^2(A, E_K)$ the variance of the neutron-number distribution for a given fragment mass A and total kinetic energy E_K, we calculate $\bar{\sigma}_\nu^2(A)$, the value of $\sigma_\nu^2(A, E_K)$ averaged over the kinetic energy distribution for a given mass. $\bar{\sigma}_\nu^2(A)$ together with $\bar{\nu}(A)$ and $(\partial\bar{\nu}/\partial E_K)(A)$ are presented in Fig. 2. $\sigma_\nu^2(A, E_K)$, $\nu(A, E_K)$, and $(\partial\bar{\nu}/\partial E_K)(A, E_K)$ are presented in Fig. 3 as a function of the mass for two kinetic energy intervals. Our $\bar{\nu}(A)$ data are in essential agreement with the results of Bowman *et al.*[2] However, the values of $(\partial\bar{\nu}/\partial E_K)(A)$ of Nardi and Fraenkel[4] are lower than ours. This is probably due to the fact that these authors had poor kinetic energy resolution because of rapid deterioration of their fission counters. (In both cases, the errors shown are statistical only and do not include systematic errors.) The high values of $\bar{\sigma}_\nu^2(A)$ and $\sigma_\nu^2(A, E_K)$ which we obtain in the mass range $123 \leq A \leq 129$ are probably due to mass dispersion effects which may result in the wrong identification of the light

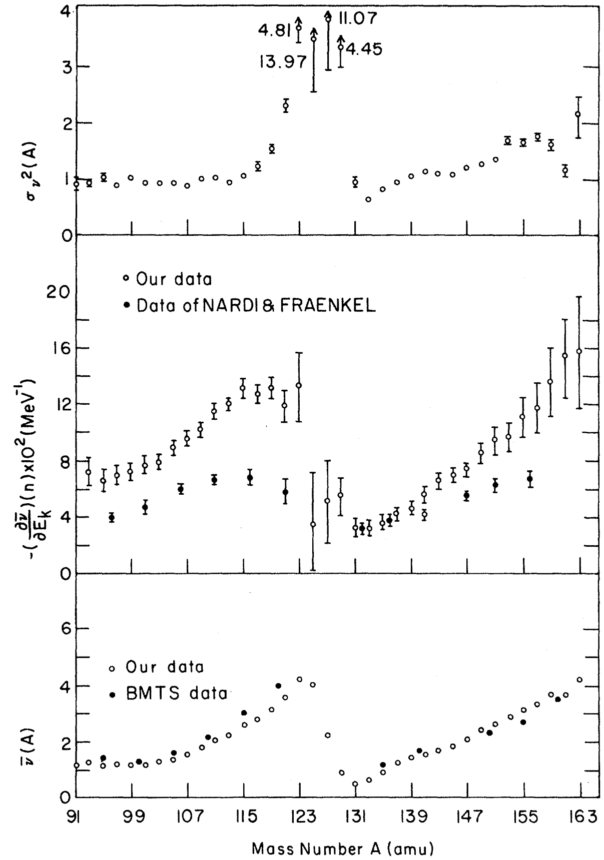

FIG. 2. Experimental results of average number of neutrons $\bar{\nu}(A)$, average derivative of the neutron number with respect to E_K, $(\partial\bar{\nu}/\partial E_K)(A)$, and the average variance of the neutron number distribution $\bar{\sigma}_\nu{}^2(A)$.

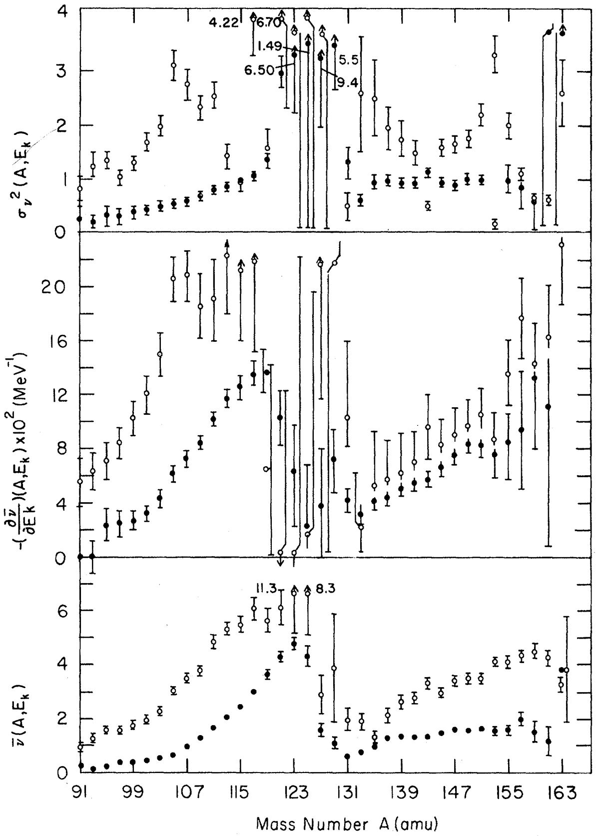

FIG. 3. Experimental results of average number of neutrons $\bar{\nu}(A,E_K)$, derivative of neutron number$(\partial\bar{\nu}/\partial E_K)(A,E_K)$, and variance of the neutron number distribution $\sigma_\nu{}^2(A,E_K)$ for two selected kinetic energy intervals. Open circles, $E_K=167-169$ MeV; closed circles, $E_K=189-191$ MeV.

and heavy fragments.

The remarkable feature seen in Fig. 2 is that $\bar{\sigma}_\nu{}^2(A)$ is practically constant $91 \leq A \leq 117$ and for $137 \leq A \leq 155$. In the same mass ranges, both $\bar{\nu}(A)$ and $(\partial\bar{\nu}/\partial E_K)(A)$ increase by at least a factor of 3. A similar feature can be discerned on the $\sigma_\nu{}^2(A,E_K)$ plot in Fig. 3, for $E_K \simeq 190$ MeV and $135 \leq A \leq 159$. In the following we show that this result implies that the correlation coefficient between the excitation energies of complementary fission fragments is substantially less than unity.

A nonzero variance $\sigma_\nu{}^2(A,E_K)$ for a selected mass A and kinetic energy E_K may be due to two possible factors. The first factor is the variance of the total fission energy released E_T due to the variation in the other parameters (such as the charge distribution). The second factor is the cross correlation between the excitation energies of the two fission fragments $[\sigma_\nu{}^2(A,E_K)$ for fixed $E_T]$. We denote by $\sigma_T{}^2(R,E_K)$ the variance in E_T for a given mass ratio R and total kinetic energy E_K. This variance of the total energy gives rise to a variance in the neutron number distribution $\sigma_\nu'^2(A,E_K)$ in each of the fragments. We calculate the dependence of $\sigma_\nu'^2(A,E_K)$ on $\sigma_T{}^2(R,E_K)$ as follows. Assuming that the number of neutrons ν emitted by a single fragment is a function of the mass number A and the total excitation energy $E_X = E_T - E_K$, we have

$$\left(\frac{\partial\nu}{\partial E_T}\right)(A,E_K,E_T) = -\left(\frac{\partial\nu}{\partial E_K}\right)(A,E_K,E_T). \quad (6)$$

In our experiment we have measured $(\partial\bar{\nu}/\partial E_K)(A,E_K)$ (the bar denoting average over E_T). We assume that the width of the probability distribution of E_T is narrow enough so that

$$\left(\frac{\partial\nu}{\partial E_K}\right)(A,E_K,\bar{E}_T) \simeq \left(\frac{\partial\bar{\nu}}{\partial E_K}\right)(A,E_K) \quad (7)$$

and

$$\nu(A,E_K,\bar{E}_T) \simeq \bar{\nu}(A,E_K). \quad (8)$$

Denoting by P the probability distribution function, we have

$$\sigma_\nu^2(A, E_K) = \int P_{A, E_K}(\nu)[\nu - \bar{\nu}(A, E_K)]^2 d\nu. \quad (9)$$

$\sigma_\nu^2(A, E_K)$ will be equal to $\sigma_\nu'^2(A, E_K)$ if we assume that $\sigma_\nu^2(A, E_K) = 0$ for fixed E_T [the distribution of $\nu(A, E_K)$ is determined entirely by E_T]. In this case we transform variables from ν to E_T using $P_{A, E_K}(\nu)d\nu = P_{A, E_K}(E_T)dE_T$. In addition we have

$$\nu(A, E_K, E_T) = \nu(A, E_K, \bar{E}_T) + \left(\frac{\partial \nu}{\partial E_T}\right)(A, E_K, \bar{E}_T)(E_T - \bar{E}_T) \simeq \bar{\nu}(A, E_K) - \left(\frac{\partial \bar{\nu}}{\partial E_K}\right)(A, E_K)(E_T - \bar{E}_T); \quad (10)$$

using Eqs. (7) and (8) we obtain

$$\sigma_\nu'^2(A, E_K) \simeq \int P_{A, E_K}(E_T)\left[\left(\frac{\partial \bar{\nu}}{\partial E_K}\right)(A, E_K)(E_T - \bar{E}_T)\right]^2 dE_T = \left(\frac{\partial \bar{\nu}}{\partial E_K}\right)(A, E_K)\sigma_T^2(R, E_K). \quad (11)$$

$\sigma_T^2(R, E_K)$ is by definition a symmetric function of the mass with respect to $A = A_0/2 = 126$, whereas $(\partial\bar{\nu}/\partial E_K)(A, E_K)$ is seen (Figs. 2 and 3) to be a highly asymmetric function of A (with respect to $A_0/2$). It follows that $\sigma_\nu'^2(A, E_K)$ must also be asymmetric with respect to $A_0/2$. Yet the experimental results of $\sigma_\nu^2(A, E_K)$ and $\bar{\sigma}_\nu^2(A)$ do not show any pronounced asymmetry as would be expected if $\sigma_\nu^2(A, E_K) \simeq \sigma_\nu'^2(A, E_K)$. It follows that $\sigma_\nu^2(A, E_K) \neq \sigma_\nu'^2(A, E_K)$, i.e., $\sigma_\nu^2(A, E_K)$ at fixed E_T is an important factor of the variance (the correlation coefficients are substantially less than +1) for at least some portions of the fragment mass-ratio distribution.

[1]J. Terrel, in *Proceedings of the Symposium on the Physics and Chemistry of Fission, Salzburg, 1965* (International Atomic Energy Agency, Vienna, Austria, 1965), Vol. 2, p. 3.

[2]H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki, Phys. Rev. 129, 2133 (1963).

[3]J. C. D. Milton and J. S. Fraser, in *Proceedings of the Symposium on the Physics and Chemistry of Fission, Salzburg, 1965* (International Atomic Energy Agency, Vienna, Austria, 1965), Vol. 2, p. 39.

[4]E. Nardi and Z. Fraenkel, Phys. Rev. Lett. 20, 1248 (1968).

[5]H. W. Schmitt, W. E. Kiker, and C. W. Williams, Phys. Rev. 137, B837 (1965).

$E4$ Moments in ^{152}Sm and ^{154}Sm†

F. S. Stephens and R. M. Diamond
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

and

J. de Boer
Universität München, München, Germany

(Received 19 July 1971)

The $E4$ transition moments between the ground state and the 4^+ rotational state in ^{152}Sm and ^{154}Sm have been determined from Coulomb excitation experiments with 10–12-MeV ^{4}He projectiles. Quantum mechanical corrections have been applied to the calculations used in the analysis of the data. The resulting $E4$ moments are about twice those expected from previously measured β_4 deformations.

In a previous paper[1] we have reported results on the $E4$ transition moment of ^{152}Sm determined by comparing the experimental and calculated yields of the 4^+ rotational state following Coulomb excitation with ^{4}He projectiles. This moment is of particular interest since it is likely to result from the intrinsic shape of ^{152}Sm and, if so, can give rather detailed information about that shape. Although data were taken on ^{154}Sm during the original experiments, these could not be interpreted because of the lack of a sufficiently accurate value for $B(E2; 4\to2)$. This $B(E2)$ value now has been measured with sufficient accuracy and, in addition, the best value for the $B(E2; 2\to0)$ of ^{152}Sm has been reviewed and adjusted slightly from the previously used value. Finally, the quantum-mechanical corrections to the cross sections have recently been calculated by Alder, Morf, and Roesel[2] for both ^{152}Sm and ^{154}Sm. Thus, the intent of this note is to present and discuss the current best values for the $E4$ moments of these two Sm nuclei.

The experiments consisted of an accurate comparison of the cross sections of the $4\to2$