The dependence of the average numbers of neutrons per fission on the ratio of masses or kinetic energies of the fragments is given in Fig. 7. It is seen that there is at most a small variation with mass ratio when no discrimination is made on the basis of total energy. However, when the fissions are first divided into two roughly equal groups with total kinetic energies greater than or less than 180 Mev, there is an obvious dependence on mass ratio (Fig. 8). The effect of the energy resolution of the apparatus has not been subtracted from these data.

Finally, the variation of the mean total kinetic energy of the fragment pairs with mass or energy ratio is given in Fig. 9.‡

ACKNOWLEDGMENTS

The work was done with encouragement of Dr. Chester M. Van Atta. We wish to thank Professor Robert Brode and Professor William B. Fretter for lending us a trailer in which to house the apparatus, Mr. Daniel O'Connell for making the source mountings, Mr. Harry Bowman for evaporating the Cf^{252}, Mr. David Johnson for reading the film, and Miss Margaret Thomas, Mrs. David McMullen, Mr. James Baker, and Mr. Charles Stableford for help with the numerical analysis. Discussions with Dr. Robert Leachman were helpful.

‡ *Note added in proof.*—H. Bowman (private communication) has carried out a similar experiment which includes a check of the present results with improved energy resolution. A partial analysis of the data indicates that there will be fairly good quantitative agreement with this work.

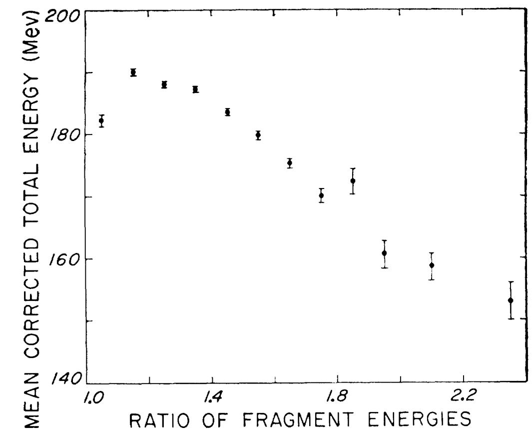

FIG. 9. The mean total kinetic energy of the fission-fragment pairs as a function of the ratio of kinetic energies of the fragments. Errors are statistical rather than absolute.

PHYSICAL REVIEW VOLUME 105, NUMBER 5 MARCH 1, 1957

Neutron Emission from Fission Modes*

R. B. LEACHMAN AND C. S. KAZEK, JR.

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received November 19, 1956)

The number and energy of neutrons and the average energy of prompt gamma rays emitted from various fission modes are estimated from the excitation-energy distributions of fragments from these modes. These excitation-energy distributions are derived from the mass equation of fission and the measured kinetic energies of the fragments. Simple considerations of neutron boil-off are used with these excitations.

For the most probable mass ratios of fragments, the variation in the average number of neutrons $\bar{\nu}$ with the total kinetic energy E_K of the fragments is found to be $d\bar{\nu}/dE_K = -0.121$ Mev^{-1} for thermal-neutron fission of U^{235} and -0.116 Mev^{-1} for spontaneous fission of Cf^{252}. The spectra of neutron energies resulting from this analysis are found to have negligible change with E_K, but the neutrons from Cf^{252} fission are more energetic than those from thermal-neutron fission of U^{235}. The average energy E_γ of prompt gamma rays from Cf^{252} fission is found to be 4.0 Mev, with a variation $dE_\gamma/dE_K = -0.0167$ for the most probable mass ratios of fragments.

INTRODUCTION

THE number and energy of neutrons emitted from fission depend in a complex manner on the excitation of the fragments, the nuclear identity of the fragments and the channels through which the excitation is expended. As an aid to understanding the detailed observations[1] of multiplicities of fission neutrons, calculations[2] have been made from a greatly simplified model of fission involving a statistical approach to the determination of the excitation and to neutron emission. In this analysis, empirical data of the energetics of fission fragments and the masses of nuclides were used to determine the distribution in total excitation energy shared by the two fragments, and then statistical assumptions were applied to estimate the distributions of excitation energy of the individual fragments and the neutron emission. The estimates of the probabilities P_ν of emitting $\nu=0$, $\nu=1$,

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] K. W. Geiger and D. C. Rose, Can. J. Phys. **32**, 498 (1954); J. E. Hammel and J. F. Kephart, Phys. Rev. **100**, 190 (1955); Diven, Martin, Taschek, and Terrell, Phys. Rev. **101**, 1012 (1956); Hicks, Ise, and Pyle, Phys. Rev. **101**, 1016 (1956); Feynman, de Hoffmann, and Serber, J. Nuclear Energy **3**, 64 (1956).

[2] R. B. Leachman, Phys. Rev. **101**, 1005 (1956).

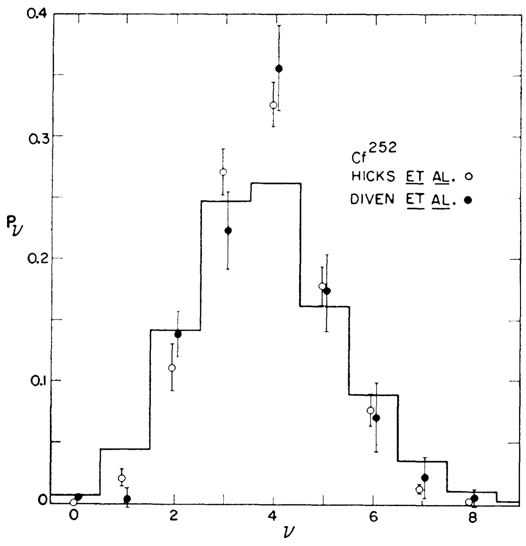

FIG. 1. Neutron emission probabilities for all modes of the spontaneous fission of Cf^{252}. Calculated probabilities are given by lines.

$\nu=2\cdots$ neutrons from fission from this analysis agreed satisfactorily with measurements.

In the present work, the same method of analysis as in reference 2 is used, but the results of neutron emission are sorted for particular fission modes. In this manner, neutron emission data are estimated for fissions resulting in certain ratios of fragment masses and certain intervals of the kinetic energy E_K of the two fragments. These results for the spontaneous fission of Cf^{252} are compared with the recent measurements by Hicks *et al.*[3]

RESULTS

To facilitate the sorting of results into those of particular fission modes, a Monte Carlo calculation of neutron emission from fission as described in reference 2 was made on IBM digital computers at Los Alamos. For the thermal-neutron fission of U^{235} the same data of fission energetics are used. However, the recent data of Smith *et al.*[4] for the energies of fragments are used to determine the excitation-energy distribution for the spontaneous fission of Cf^{252}. As was previously discussed,[2] a dispersion $D(E_K,E_I)$ relating the observed kinetic energy E_I and the true kinetic energy E_K of the fragment pairs is to be removed from the data. The dispersion width u in

$$D(E_K,E_I)\propto\exp\left[-\left(\frac{E_I-E_K}{u}\right)^2\right] \qquad (1)$$

has not been determined for these data, but a width $u=5.2$ Mev was estimated from ion-chamber calibrations[5] and from considerations of fragment recoil during neutron emission.

These data in the Monte Carlo analysis for all fission modes of Cf^{252} result in the neutron multiplicities shown in Fig. 1 when the "temperature" $T=1.4$ Mev is used in the neutron boil-out relation

$$n(\epsilon)\propto\epsilon\exp(-\epsilon/T), \qquad (2)$$

where $n(\epsilon)$ is the emission probability for neutrons of energy ϵ. In this analysis, the reported total energies of the fragments were all decreased by 4.6 Mev to result in a calculated $\bar{\nu}=3.82$. The agreement with experimental data of P_ν is considered to be satisfactory.

A sorting of fissions of mass ratios near the most probable R_A into intervals of kinetic energy E_K results in a linear relation of $\bar{\nu}$ as a function of E_K, as given in Table I. The dependence of $\bar{\nu}$ on E_K for U^{235} fission is shown in Fig. 2. In the Monte Carlo calculations, a sufficient number of fission trials were made to result usually in more than 3×10^4 fissions satisfying the interval requirements. It can be shown that the calculated $d\bar{\nu}/dE_K$ is insensitive to the value of u used in (1).

TABLE I. The variations of the average number of neutrons $\bar{\nu}$ with the kinetic energy E_K of the fragments for the most probable mass ratios R_A of fission. The "temperature" of neutron emission is given by T.

Fission case	R_A	T (Mev)	$d\bar{\nu}/dE_K$ (Mev^{-1})
U^{235}+thermal neutrons	141/95	1.4	−0.121
		1.0	−0.130
Cf^{252}	145/107	1.4	−0.116

In the case of Cf^{252} fission the calculated $d\bar{\nu}/dE_K=-0.116$ Mev^{-1} is considerably greater than the -0.055 Mev^{-1} observed by Hicks *et al.*,[3] implying a large dispersion in their observations of fragment kinetic energies. As pointed out by these authors, a dispersion of $u=12$ Mev in their measurements of E_I combined with the inherent distribution in E_K would account for this difference in $d\bar{\nu}/dE_K$ values. The calculated $\bar{\nu}=4.27$, $\bar{\nu}=3.82$, and $\bar{\nu}=3.49$ for mass ratios near $R_A=139/113$, $R_A=145/107$, and $R_A=154/98$, respectively, and for all E_K values are not inconsistent with these measurements. These $d\bar{\nu}/dE_K$ results differ from the nearly constant $\bar{\nu}$ as a function of E_K deduced by Fraser and Milton[6] from measurements of the energies of U^{233} fission fragments and neutron emission probabilities.

In the calculations, the neutron emission energies ϵ are transformed to the laboratory system through the use of an assumed isotropic angular distribution. As was previously discussed,[2] this method of estimating the fission-neutron spectrum is sensitive in the low-energy region to the angular distribution assumed and in the high-energy region to the low-energy tail of the

[3] Hicks, Ise, Pyle, Choppin, and Harvey, preceding paper [Phys. Rev. **105**, 1507 (1957)].
[4] Smith, Friedman, and Fields, Phys. Rev. **102**, 813 (1956).
[5] A. B. Smith (private communication, 1956).
[6] J. S. Fraser and J. C. D. Milton, Phys. Rev. **93**, 818 (1954).

fragment kinetic energies. Thus, the results are considered to be reliable only for comparing the spectra resulting from fissions of one type of nucleus and not for comparing the spectra from different types with their different measurements of fragment energies.

In Fig. 3 are shown the resulting spectra for various fragment energy intervals for the most probable mass-ratio region of Cf^{252} fission and thermal-neutron fission of U^{235}. In the calculations, an isotropic angular distribution of neutrons from the moving fragments was used. Also, $T=1.4$ Mev was used, although $T=1.0$ Mev has been shown[2] to result in better agreement with measurements. The similarity of the spectra of each case is to be noted. Although not shown in the figure, the composite of the calculated neutron spectra from all modes of fission of each nucleus is the same as for the selected modes. Qualitatively, the observed[7] 9% higher energies of neutrons from Cf^{252} fission than from neutron-induced fission of U^{235} are to be expected from the larger velocities and greater excitations of the fragments. The calculations indicate the average energy of neutrons from Cf^{252} is 21% greater than from thermal-neutron fission of U^{235}. In the present analysis, the larger energies of Cf^{252} neutrons might also be due to the distribution in the excitation energy used. The wide calculated distribution in P_ν in Fig. 1 indicates that the E_I data of Cf^{252} require a larger value of the dispersion width u, the use of which would result in fewer high-energy neutrons.

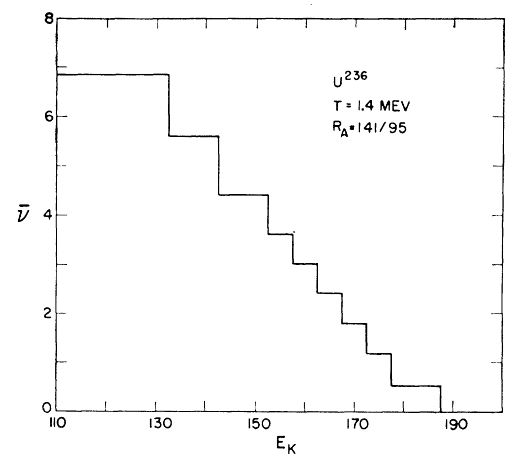

FIG. 2. Calculated average number of neutrons $\bar{\nu}$ from thermal-neutron fission of U^{235} for modes resulting in intervals of kinetic energy E_K. Calculations are for ratios of fragment masses near the most probable mass ratio.

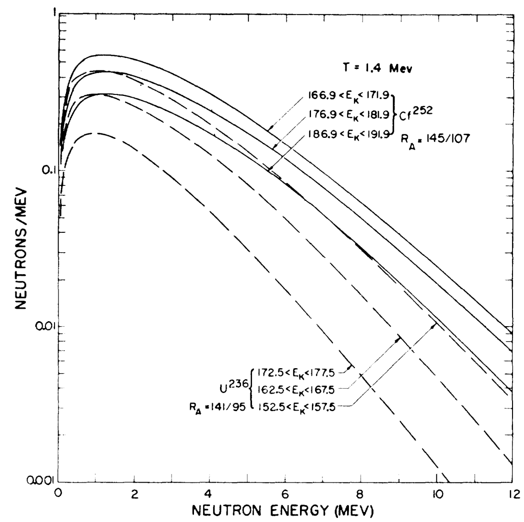

FIG. 3. Calculated neutron spectra for modes of spontaneous fission of Cf^{252} and thermal-neutron fission of U^{235} with mass ratios near the most probable mass ratios. As discussed in the text, all the difference between the U^{235} and Cf^{252} data is not necessarily real.

As in the previous calculations,[2] the average energy E_γ of the prompt gamma rays from fission is determined from the residual excitation energy after all the neutrons have been emitted. For Cf^{252} fission this results in $E_\gamma=4.0$ Mev, which is low compared to measurements of 8 and 9 Mev.[8] This difference is outside of the stated experimental errors and cannot be eliminated by reasonable variations in the calculation variables T and u. If real, this difference implies the necessity for a significant change in the neutron emission expression (2) or in the binding energy of the last neutron. In this connection, Milton[9] has mentioned the possibility of gamma rays competing favorably with neutron emission from the distorted nuclei of the fragments.

A small variation of E_γ with the Cf^{252} fission modes for mass ratios near $R_A=145/107$ is found in the calculations. This variation is $dE_\gamma/dE_K=-0.0167$.

ACKNOWLEDGMENTS

The authors wish to thank R. V. Pyle for suggesting the present calculations and P. E. Harper and M. Goldstein for assistance in the calculations.

[7] Hjalmar, Slätis, and Thompson, Arkiv Fysik **10**, 357 (1956).

[8] Smith, Fields, and Friedman, Phys. Rev. **104**, 699 (1956) and H. R. Bowman and L. G. Mann, Phys. Rev. **98**, 277 (1955) (revised to 9 Mev in a private communication in 1956).

[9] J. D. C. Milton, Chalk River Report CRP-642-A, 1956 (unpublished).