PROMPT FISSION YIELDS AND TOTAL KINETIC ENERGY BEHAVIOR FROM TIME-OF-FLIGHT MEASUREMENTS

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An improved version of the time-of-flight apparatus described previously[1,2] has been used to study the thermal neutron fission of U^{233}, U^{235}, and Pu^{239} using a neutron beam of intensity about 10^9 neutrons sec^{-1} cm^{-2} from the NRU reactor. The sources, ranging from 20 to 40 μg cm^{-2}, were electrosprayed onto two cross-laminated VYNS films of total surface density 7 μg cm^{-2} which had been previously coated with 18 μg cm^{-2} of gold to make them electrically conducting. The energy loss caused by source and backing thickness was measured for the actual sources used in the experiment and found to be 1.1 ± 0.3 Mev in good agreement with the value calculated from the known thicknesses.

The fragments were detected at the end of their nearly equal 178-cm flight paths by 4-inch diameter secondary electron detectors which gave the apparatus a resolving time (FWHM) of 2.5 nanoseconds. The mass resolution including the contribution of timing jitter, recoil from neutrons, and source thickness was calculated to be 2 mass units.

In all, well over 10^6 events were processed on $U^{235}+n$ (including some with the unequal flight paths of 270-180 cm) but the most carefully controlled series consisted of 1.48×10^5, 1.55×10^5, and 1.03×10^5 events for U^{233}, U^{235}, and Pu^{239}, respectively, and it is on this set that the data presented here are based. The experimental results on Cf^{252} are not new but are those of reference 1.

An experiment of this type conveys an enormous amount of information. The purpose of this Let-

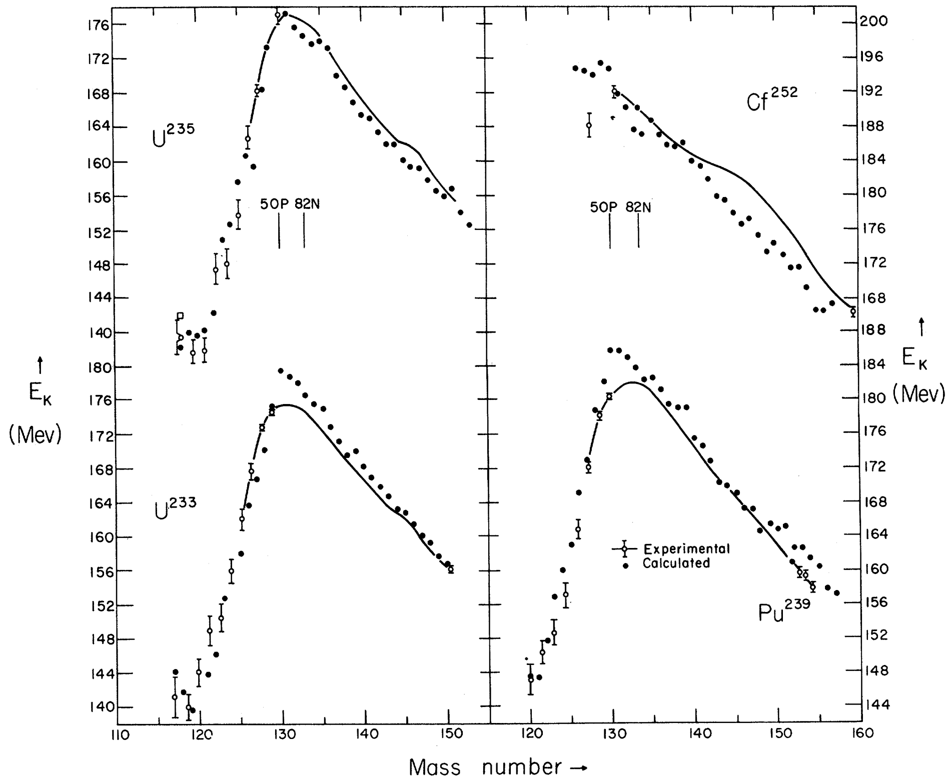

FIG. 1. The average total kinetic energy as a function of the mass of the heavy fragment. In the mass region 130-150 the experimental curve is determined by over 20 points, each with a statistical error of less than 0.25 Mev.

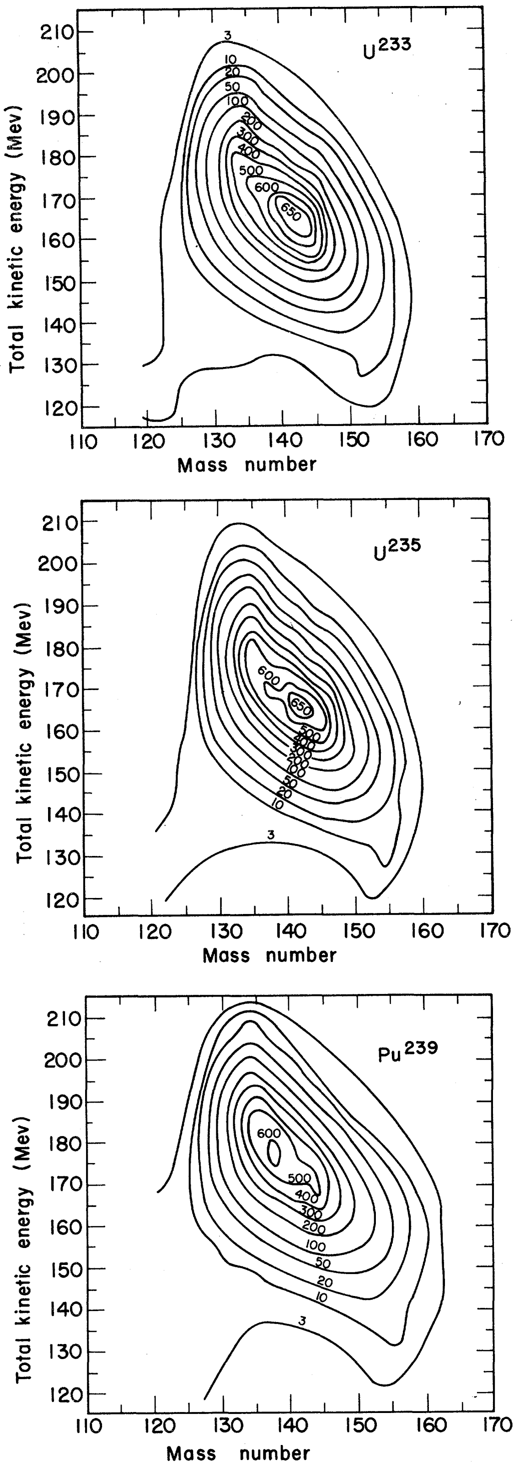

FIG. 2. Mass-energy contours for U^{233}, U^{235}, and Pu^{239}. The numbers attached to the contours are events $(10^5 \text{ fissions})^{-1}$ (mass unit)$^{-1}$ (2.5 Mev)$^{-1}$. Some idea of the statistical accuracy may be gained from the fact that the number of events in each cell of the matrix from which the contour diagram was made is approximately $2\frac{1}{2}$ times the contour label.

ter is to note 3 points: (1) There is a dramatic drop in the total kinetic energy near symmetry; (2) there is a clearly marked fine structure in the mass yield which is most prominent at high total kinetic energies; and (3) a possible explanation for the phenomenon (1).

The behavior of the kinetic energy is illustrated in Fig. 1. Except in the case of Cf^{252}, there is a drop in kinetic energy of 30-40 Mev in approaching symmetric mass division. At first it seemed impossible to account for this dip in terms of the balance of energy between the mass energy release E_R, and the excitation energy made up of components E_B (neutron binding), E_{nk} (neutron kinetic), and E_γ (gamma rays), but this turned out to be incorrect. The solid points in Fig. 1 are calculated from the formula $E_K = \max\langle E_R\rangle - \nu(\langle E_B\rangle + E_{nk}) - E_\gamma$. The quantities E_{nk} and E_γ were assumed to be independent of mass and given the approximate values $E_{nk} \approx 1.2$ Mev, $E_\gamma \approx 7.5$ Mev. The averages were taken over a Gaussian charge distribution with an rms deviation of 0.7 charge unit. Using the mass formula of Cameron,[3] $\langle E_B\rangle$ was found at the point where $\langle E_R\rangle$ had its maximum value. These quantities have been calculated for 25 fissioning species between Ra^{226} and Fm^{254} using an IBM-709 computer. However, the principal difference between the E_K calculated here and those done previously lies in the selection of ν. It was assumed that ν depends only on the mass of the fragment and not on the fissioning nuclide. This may be seen to be a good assumption by looking at the values of ν calculated by Terrell.[4] Accordingly, a smooth curve was drawn through Terrell's family of curves. The values of $\bar{\nu}$ given by this smooth curve are 2.50, 2.63, 2.86, and 3.81 for U^{233}, U^{235}, Pu^{239}, and Cf^{252}, respectively. This procedure makes ν available for all masses between 82 and 159 with the exception of the region 120 to 130. In this region the two ends of Terrell's curve were joined by a straight line. At first sight this may seem to be a very shaky business but, in fact, almost any interpolation between Terrell's two curves will do since in U^{235} (for example) it affects the shape of the kinetic energy between mass 130 and 118 but not the value at these two masses. There would still be a drop of nearly 40 Mev, even if ν were taken as identically zero for the region 121-130.

The total excitation energies at symmetry predicted by this picture are large, about 48 Mev for U^{235} and about 6 neutrons would be expected. The existence of two types of fission—symmetric fission with highly excited fragments of low kinetic energy and asymmetric fission with moderately excited fragments of high kinetic energy—might be associated with the existence of two barriers and two saddle-point configurations in the liquid drop calculations of Cohen and Swiatecki.[5] The height of the second barrier relative to the first falls rapidly as x increases above a critical value in the vicinity of 0.7 and its relatively low energy and apparent stability against asymmetry[5] suggest identifying this barrier with symmetric fission.

All three of the fissioning species showed fine structure in the mass yield between masses 134 and 146. This fine structure shows up in the total yields[6] but it is perhaps more instructive to look at the contour diagram, Fig. 2. Here it is clearly seen that the structure appears predominantly at high kinetic energies.[7] It seems to be more a result of inhibition than of preference and must be closely related to the fact that the events in this region are "running out of energy" so that the nuclei formed are nearly in their ground states. The contours along the northeast face of the mountain are nearly parallel to the line of maximum energy release. The structure is less pronounced in Pu^{239} and scarcely discernible in Cf^{252}. In these cases the mountain is further away from the limiting energy.

A full account of this work will shortly be submitted to the Canadian Journal of Physics. I am indebted to Dr. W. J. Swiatecki for pointing out the connection with the liquid drop calculations.

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[6] J. C. D. Milton, Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 866.

[7] This is also shown in the work of W. M. Gibson, T. D. Thomas, and G. L. Miller, preceding Letter [Phys. Rev. Letters 7, 65 (1961)].

DEUTERONS FROM HIGH-ENERGY PROTON BOMBARDMENT OF MATTER

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The mass analysis of the secondary particles from targets exposed to the 25-Bev proton beam of the CERN proton synchrotron has revealed an appreciable fraction of high-energy deuterons.[1] In addition large numbers of deuterons have been reported among the "grey" tracks in nuclear emulsions.[2-4]

Recently Hagedorn[5] has suggested that these deuterons are produced in elementary nucleon-nucleon collisions. However, the results obtained from a statistical model are strongly energy dependent and especially at lower energies it is hard to reconcile them with the experimental results. For deuterons with momenta below 2 Bev/c they disagree with experiment by a factor greater than 10^3.

In interpreting the emulsion results the Bristol group suggested that the deuterons are formed when a knock-on nucleon pairs with a nucleon in the tail of the Fermi distribution of the excited nucleus. Because of their high energy, however, it seems more likely that they result from the pairing of two cascade nucleons. The angular distribution of the knock-on "shower" nucleons has a strong forward peak and in many cases there will be pairs of particles which have small relative momenta. It is from such pairs that we believe deuterons are formed.

To calculate the ratio of deuterons to protons expected from such a process, we have considered the following model. An incident beam of free protons and neutrons is scattered by an effective nuclear potential, which represents the interaction of the high-energy cascade nucleons with the remainder of the nucleus. The protons and neutrons can interact with each other during the scattering. The incident particles are not parallel or monoenergetic, but have a certain momentum distribution, say $P(\vec{k})d\vec{k}$, which is the same for neutrons and protons and fits the experimental distribution for cascade protons. The flux of particles in the incident beam is chosen to yield n_0 nucleons of each type contained in the nuclear volume at any one time, where n_0 is the experimental average number of high-energy protons from a struck nucleus.