this fact in mind. It may be noted, for example, that the electronic configuration of an alkali impurity in a rare gas solid is precisely analogous to that of a donor in a semiconductor. Undoubtedly the effective masses of conduction electrons in other rare gas solids can be determined by proper choices of impurities.

The authors have enjoyed fruitful discussions with Professor A. Gold and Professor K. Teegarden of the Institute of Optics, and acknowledge the assistance of Mr. J. O'Brien in carrying out the measurements.

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[6]See, e.g., W. Kohn, in Solid State Physics, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1957), Vol. 5, p. 257. In our case the positive charge involved is a trapped hole rather than an excess charge on the donor nucleus.

[7]See reference 1 for a discussion of this quantity and for further references.

[8]The mass observed may well be that of a "clothed" electron, i.e., the "electronic polaron" [Y. Toyozawa, Progr. Theoret. Phys. (Kyoto) 12, 421 (1954)]. Weak-coupling polaron theory is probably valid in solid argon, since the coupling constant α is only 0.4. In the present case the measured "bare" mass is then $(1-\alpha/6)\times(0.46)=0.43$ electron masses.

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TERNARY FISSION OF U^{235} INDUCED BY THERMAL NEUTRONS*

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Studies of the ternary fission process in which a heavy nucleus divides into three charged fragments of large mass have been reported using nuclear emulsion techniques and, in one instance, electronic counting methods.[1] However, the limitations of standard nuclear emulsion techniques make it difficult to distinguish between ternary fission events and recoil phenomena; likewise, past limitations on coincidence resolution times coupled with the infrequency of occurrence of ternary fission has heretofore prevented any direct measurement of this process. As a result, the existence of the ternary fission process at low excitation energies has not gained general acceptance.

The purpose of the present investigations is twofold: (a) to establish with confidence the existence of ternary fission, and (b) to study the mass-energy-angular correlations of tripartite mass division in the fission process. The present note is intended mainly to present preliminary data on the mass yield distribution and total kinetic energy release in ternary fission of U^{235} induced by thermal neutrons.

The experimental arrangement consisted of three solid state detectors positioned 120° apart in a plane about a fission source made by evaporating a film of $U^{235}F_4$ (5-300 $\mu g/cm^2$) onto a thin (60 $\mu g/cm^2$) nickel foil support. The detectors and source were enclosed in an evacuated aluminum chamber and placed in the thermal column of the University of Florida Training Reactor (UFTR). The detectors were of the surface barrier type fabricated from 300 ohm-cm silicon and operated at 30 volts back bias voltage. Calibration was accomplished before and after each experiment by comparing the binary fission fragment energy spectrum to that obtained from time-of-flight data[2] and extrapolating to lower energies using the average light- and heavy-mass energy positions. The output pulse of each of the three detectors was paralleled to a fast triple coincidence system and (after amplification) to a three-coincident-parameter analyzer[3] having $256\times256\times256$-channel resolution. The analyzer was triggered by the coincidence unit and, hence, recorded only those events in which a fission fragment entered each detector within the resolving time of the coincidence unit (5 nsec). This instrumentation and the experimental arrangement

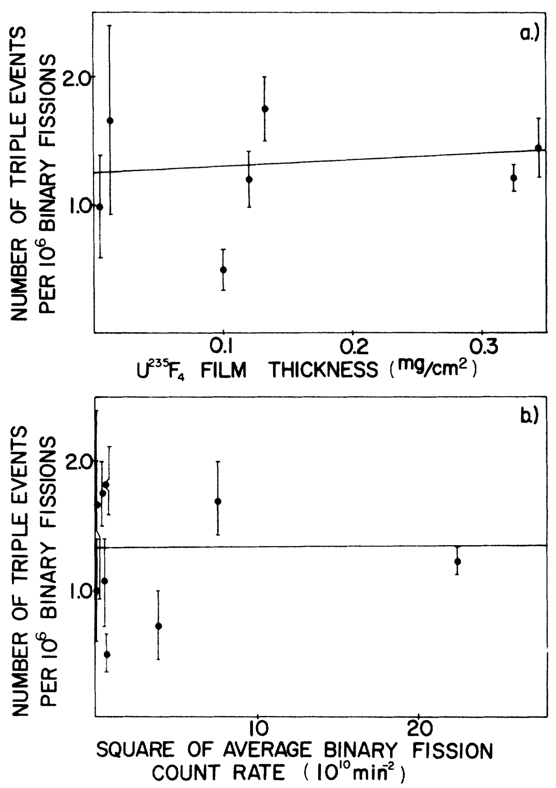

FIG. 1. Relative frequency of triple events as a function of (a) $U^{235}F_4$ foil thickness, and (b) square of binary fission count rate. The straight line is a least-squares fit. Error bars represent statistical errors of counting.

differ from previously used methods in that (a) nanosecond triple coincidence time resolution (2 nsec minimum) is used to distinguish ternary fission events from accidentals, (b) an energy analysis of the three fragment energies is simultaneously conducted in parallel with the detection of the ternary fission events, and (c) the solid angle (0.25 sr) subtended by each detector is better defined. This last condition serves in part to eliminate (on the basis of energy-momentum considerations) the possibility of false triple events due to fission fragment scattering with medium- and light-mass nuclei, viz., nickel and fluorine nuclei.

The plot in Fig. 1 demonstrates the nondependence of the relative frequency of occurrence of ternary fission on (a) the source foil thickness and (b) the square of the single count rate, thus experimentally establishing the triple coincidence count rate as resulting from ternary fission events rather than scattering or accidental events, respectively. A straight line plot, passing through the origin, should result if the triple events are caused by either of these two factors. A lower limit of 1.2 ternary fission events per 10^6 binary fission events is indicated.

The total fragment kinetic energy spectrum is shown in Fig. 2(a). A marked decrease in the total fragment kinetic energy release is featured; an average value of 142 MeV is observed. The explanation for this characteristic would appear to lie in the fact that, in order to achieve a repulsion of the three fragments into the detectors (placed 120° apart), axially asymmetric distortions must be achieved at least in the latter stages of the fission process (i.e., just prior to scission). Hence it would be expected that considerable energy is tied up in the form of deformation energy at the scission moment. One might visualize the distortion as resulting in a configuration somewhat as shown in Fig. 3. For a static configuration of this type, the decreased fragment kinetic energies result from a relatively larger separation of charge centers as scission occurs.

The individual mass spectrum is shown in Fig. 2(b). The maximum mass dispersion due to one detector is approximately 20 mass units; hence any mass fine structure present is submerged. Nevertheless, a general range of masses from approximately 30 to 130 mass units is observed for the ternary fission process.

It should be emphasized that the data recorded in these experiments [Fig. 2(a) and (b)] are char-

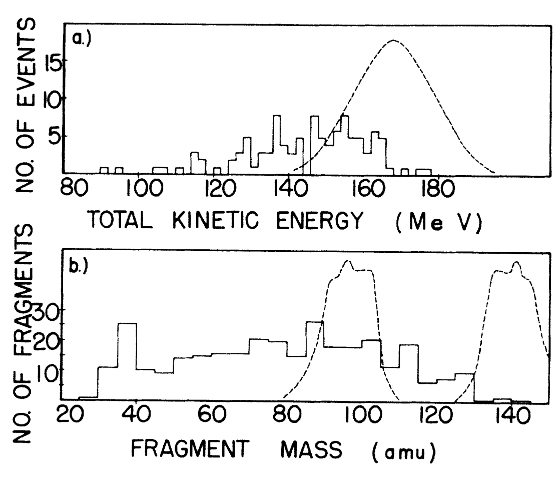

FIG. 2. (a) Total energy distribution in ternary fission of U^{235} + neutron. The dashed curve represents the total energy distribution (arbitrary scale) for binary fission taken from reference 2. (b) Mass yield distribution in ternary fission of U^{235} + neutron. The dashed curve represents the primary mass yield (arbitrary scale) for binary fission taken from reference 2.

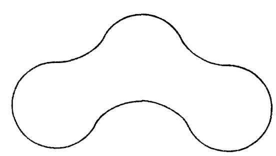

FIG. 3. Diagram showing a possible off-axial static configuration for the ternary fission process. A distortion such as depicted here is proposed to account for tripartition in which the fragment masses are repelled at 120° from each other. Off-axial distortions may also be a contributing factor in the binary fission process.

acteristic only of ternary fission in which the fragment masses are repelled at approximately 120° from each other. Experiments are in progress to determine the angular correlation of these properties (mass, energy).

Summarizing, the following hypotheses are suggested by the data:

(1) The existence of ternary fission in which the fragment masses are repelled at angles 120° apart implies an axially asymmetric distortion at the moment of scission (see Fig. 3). Assuming that ternary fission is not represented by a uniquely different "mode" of distortion (as compared to that describing the binary process), the presently accepted models (based on axially symmetric distortions) explaining the fission process may perhaps be misleading. It is tempting to suggest that the amount of off-axial distortion at the scission moment may be a more realistic parameter for correlating the total fragment kinetic energy release in binary fission.

(2) The markedly smaller total kinetic energy release (142 MeV as compared to 168 MeV for binary fission) coupled with the infrequency of occurrence suggests a kinship between the distortion configurations of ternary fission and binary fission of the symmetric (mass division) type for which similar properties are observed. Finer mass resolution studies of the ternary fission process and greater statistical accuracy should shed more light on this possible connection.

(3) Since it is apparent that a large amount of energy must appear as potential energy of deformation in order to effect ternary fission, the frequency of this mode of decay relative to binary fission is expected to increase with increasing excitation energy of the initial compound nucleus system (as is also the case with symmetric binary fission).

(4) The increase (about 30-35 MeV) in the mass-energy release for the ternary fission process coupled with the observed decrease (about 20 MeV) in the total fragment kinetic energy should yield an unusually large amount of resultant fragment excitation energy (perhaps as high as 50-55 MeV total; underlying shell structure effects may vary this value somewhat). For a distortion mode similar to that shown in Fig. 3, the middle fragment will receive the largest share of this excitation energy by virtue of the fact that it is the most highly deformed. Such an excess of excitation energy may be sufficient (through neutron evaporation) to move one or more primary mass fragments to the line of beta stability resulting in nonradioactive fission products.

The above considerations are based on a static configuration of the nucleus at the moment of scission; however, the essential features outlined above should not be grossly affected by a more realistic yet unwieldy dynamic model.

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