prediction, supports qualitatively this appearance of collective effects in the shell model calculations. This effect is discussed in detail by Elliott[11,12] who demonstrates certain collective features in shell-model wave functions which form representations of the group $U(3)$. The mean life for the $3+$ to $1+$ transition in F^{18} can be calculated from the $U(3)$ wave functions given in Ref. 11, and the value obtained, using the same values of the parameters as in the shell-model calculations above, is $\tau_m = 0.54 \times 10^{-10}$ sec, which is close to the shell-model value and is again consistent with the present upper limit. Clearly, an actual measurement of this lifetime would be valuable.

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Fine Structure Effects in the Fission of U^{235}†

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By the use of a Frisch-gridded double ionization chamber the energy and mass distribution of U^{235} fission fragments under thermal neutron fission have been studied in coincidence with relatively high-energy prompt-fission γ rays. The data were electronically analyzed and the results printed on paper tape, transferred to IBM cards, and analyzed by the campus IBM-7074 computer. Runs were taken for fission fragments in coincidence with prompt-fission γ's>2 MeV and γ's>3 MeV and the results were compared with fission fragments corresponding to all γ rays. Pronounced structural effects were noted in the kinetic-energy distribution and in the mass ratio, the magic-number nucleus $N=82$, $Z=50$ perferentially emitting higher energy γ rays. The symmetric fission yield was found to increase the γ-ray energy, thus offering the possibility that the extra excitation energy of symmetric fission fragments may be carried off in the form of higher energy γ rays.

INTRODUCTION

RECENTLY, several experiments have been performed with the purpose of looking for fine structure effects in fission. Gibson *et al.*[1] found such an effect in the kinetic-energy spectrum of the heavy fission fragments of U^{235} in coincidence with different light-fragment energies. It was also noticed that the total kinetic-energy release for symmetric fission is approximately 30 MeV less than for asymmetric fission,[2] and that the number of neutrons emitted for symmetric fission of U^{235} is ~ 6 (compared to the average of 2.5). This higher rate of neutron emission may help carry away some of the extra excitation energy in the case of symmetric fission but possibly some of it might also appear as higher energy γ radiation. In addition, Vandenbosch[3] suggests that the dip in the kinetic energy and the sawtooth structure in the prompt neutron yields[4] result from the influence of the shell structure of the eventual fragments at the scission configuration. Milton and Fraser[5] found that for Cf^{252} the yield of γ rays showed a pronounced dip at the doubly magic-number nucleus $N=82$, $Z=50$ with the average γ-ray energy being slightly higher in this region. In this experiment the kinetic energy, mass, and angular distribution of the fission fragments arising from the thermal neutron fission of U^{235} have been studied in coincidence with relatively high-energy prompt fission γ rays with the purpose of looking for fine structure effects if they exist.

EXPERIMENTAL METHOD AND PROCEDURE

In carrying out this experiment a Frisch-gridded double ionization chamber was constructed in a manner similar to one developed previously by one of the authors.[6] The gas mixture in the chamber consisted of

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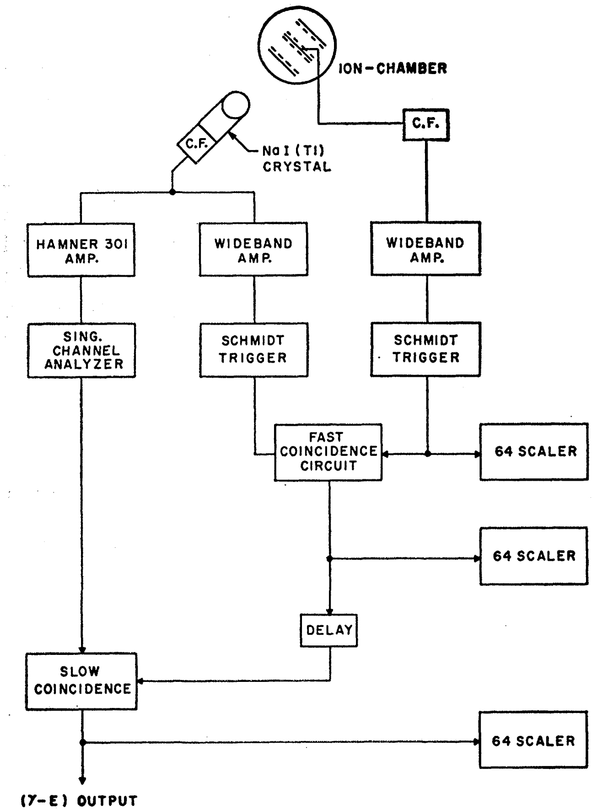

FIG. 1. Fast-slow coincidence circuit.

93% argon and 7% CO_2 in order to collect the electrons produced by the passage of the fission fragments through the gas in the shortest possible time (0.15 μsec). The chamber was operated at saturation voltage and slightly less than atmospheric pressure. A thin metalized plastic foil with a deposit of 25 $\mu g/cm^2$ of U^{235} was placed in the center of the anode and a collimated beam of thermal neutrons of $10^5 n/cm^2$ sec obtained from the Penn-State Reactor was used to produce the fission.

Figure 1 shows the fast-slow coincidence circuit set up between the pulse produced by the electrons collected on the anode and the fission γ rays. The relatively slow collection time of the electrons, 0.15 μsec, placed a limit on the resolution time of the circuit. A 3-in.×3-in. NaI(Tl) crystal placed parallel to the electric field was used in order to detect the fission γ rays. The Baird Atomic 510 single-channel analyzer in this circuit was

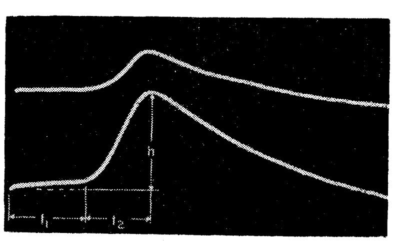

FIG. 2. Photograph of + ion pulses. The trace is triggered by the $(\gamma-e)$ coincidence pulse.

operated in the integral position allowing all fission γ rays above the chosen energy to pass through. Tests were run in which all fission γ rays starting from 25 keV and above were counted and the results were compared with runs in which only γ's>2 MeV and γ's>3 MeV were taken into account. At the same time the positively charged slowly moving argon and CO_2 ions produced by the two fragments on opposite sides of the chamber were collected by their respective cathodes in a few milliseconds. The output trigger of the $(\gamma-e)$-coincidence circuit opens a gate circuit allowing the pulses produced by the collection of the positive ions to be analyzed by the recording apparatus.

Figure 2 shows the positive ion pulses collected at the cathodes, the time base of the oscilloscope being triggered by the output of the $(\gamma-e)$ coincidence circuit. The delay time t_1 is the time between the $(\gamma-e)$ coincidence pulse and the time it takes for the first of the positively charged argon ions to reach the cathode, t_2 is the collection time, and h is the height of the pulse being approximately proportional to the

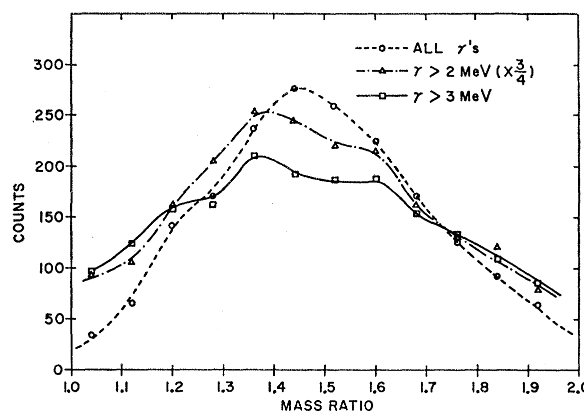

FIG. 3. Mass ratio of fission fragments.

energy of the fragment. As shown in the earlier work[6] the times t_1 and t_2 can be used to determine the angle of emission of the fission fragments with respect to the electric field.

The times t_1 and t_2 were recorded by H. P. 522 *B* counters while the pulse height h was converted to a dc voltage proportional to the peak of the pulse and recorded by an H. P. 405 AR Digital Voltmeter. This information was sent into a Dymec Scanner and then into an H. P. 560 A Digital Recorder which printed the information on paper tape. Both positive ion pulses were analyzed by the same method. The information was then placed on IBM cards and analyzed by the campus IBM-7074 computer. Approximately 50 000 events were analyzed in this manner.

RESULTS AND DISCUSSION

As a relatively thick source was used there was some attenuation in the energy of the fragments passing

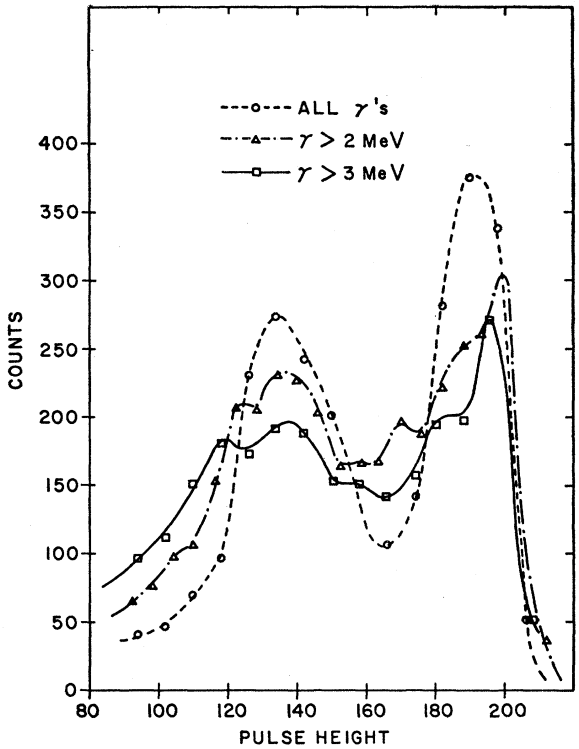

FIG. 4. Energy distribution of fission fragments.

through the foil with a consequent error in the peak-to-valley ratio in the mass distribution. However, the same peak-to-valley ratio was obtained for repeated tests when operating the single-channel analyzer in the open position (i.e., allowing all fission γ's to pass through). Comparing these results with those obtained for $\gamma>2$ MeV and $\gamma>3$ MeV a systematic increase in the amount of symmetric fission was noticed. In addition, pronounced fine structure effects were seen in the kinetic-energy distribution of the fragments as well as in the mass ratio yield (Figs. 3 and 4). In Fig. 3 a rather pronounced hump appears corresponding to a ratio of about 1.35 which is at the doubly magic nucleus $N=82$, $Z=50$. The results for the kinetic energy distribution consists of two superimposed components.

Because of the slow collection time of the electrons at the anode the $(\gamma-e)$ coincidence time is limited to ~ 0.2 μsec, which allows for a relatively large amount of accidental coincidences between the fission electron pulse and a random γ ray coming from the reactor core or from (n,γ) reactions in the surrounding material. Since there is no correlation in the case of the accidentals this would tend to produce the standard double humped energy curve corresponding to that shown in Fig. 4 for all γ rays. Thus, the results for $\gamma>2$ MeV and $\gamma>3$ MeV consist partly of the standard double-humped energy curve and superimposed upon it the results for the true coincidences—i.e., the fragment energy distribution for those fragments in coincidence with prompt fission γ's>2 MeV and γ's>3 MeV. This was verified by taking several runs with different $(\gamma-e)$ coincidence times. For a smaller coincidence time, we should obtain a smaller percentage of accidentals and therefore a smaller amount of the standard double-humped curve. This was actually observed as the structural effects became more pronounced for a smaller $(\gamma-e)$ coincidence time. Except for a small increase in the half-width and a slight downward shift in energy, no major effect was observed in the total kinetic-energy distribution, while a small amount of anisotropy was found in the angular distribution.

In conclusion, the increase in the symmetric yield seems to show that higher energy γ rays are more likely emitted in the case of symmetric fission thus offering a partial means of getting rid of the extra excitation energy. Also the doubly magic-number nucleus $N=82$, $Z=50$ appears to emit higher energy γ radiation in agreement with the results of Milton and Fraser[5] for Cf^{252}. Finally, while a very pronounced fine structure appears in the kinetic-energy distribution of the fragments almost no effect is seen in the total kinetic-energy distribution.

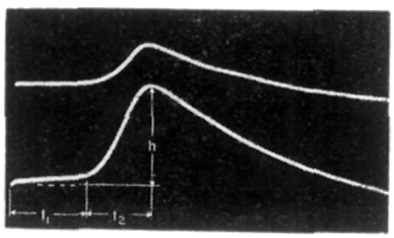

FIG. 2. Photograph of + ion pulses. The trace is triggered by the $(\gamma-e)$ coincidence pulse.