coefficients of McGowan are interpreted using Sliv's[13] calculated K-conversion coefficients, the 208-kev transition is found to be an $E1+M2$ mixture with $Q_1 \leqslant 0.009$, and the 113-kev transition is an $M1+E2$ mixture with $0.896 \leqslant Q_2 \leqslant 0.994$. These are in agreement with conversion ratio measurements by Wiedling.[14] Figure 2 illustrates a $9/2(D,Q)9/2(D,Q)7/2$ cascade. It is seen that the experimental A_2 coefficient is consistent with a $9/2(D,Q)9/2$ assignment for the 208-kev gamma with any value of Q_1. However, the absence of an A_4 coefficient from the angular correlation requires a small value for Q_1. The angular correlation is then clearly consistent with the conversion data. Both the angular correlation and the conversion data will also fit a $7/2(D,Q)9/2(D,Q)7/2$ sequence, but this possibility has been eliminated by Wiedling on the basis of other data.[14] Thus the angular correlation confirms the spin assignment of 9/2 for the 321-kev level in Hf^{177} and the predominantly dipole character of the 208-kev transition.

[13] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICC Kl, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)]. Klema did not use Sliv's tables and also omitted the limits of error from his interpretation.

[14] Tor Wiedling, *Directional Correlation Measurements and Some Other Related Investigations of Excited Nuclei* (Almquist and Wiksells Boktryckeri AB, Uppsala, 1956).

TABLE I. Measured K-conversion coefficients for the 208-kev and 113-kev gamma rays in Hf^{177}.

E_γ (kev)	McGowan *et al.*	Marmier and Boehm
208	0.042 ± 0.015	0.044
113	$0.81\ \pm0.08$	0.75

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Thermal-Neutron-Induced Fission of Th^{229}

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A back-to-back ionization chamber is used to measure the Th^{229} fission fragment kinetic energy distribution. This fission process is found to be the most asymmetric known, with a most probable mass ratio of 1.57. The measured total fragment energy is 160.2 ± 3 Mev. The experimental results are compared with the characteristics of other fission processes and with theory.

INTRODUCTION

BY far the largest fraction of the energy available at fission goes into the violent kinetic motion of the massive fragments. Many workers have experimentally studied this kinetic fragment energy.[1–5] These investigations have dealt with spontaneous and thermal-neutron-induced fission of uranium and transuranium isotopes. From these experiments it is evident that the fission symmetry and total fragment kinetic energy increase as the mass of the fissioning nucleus becomes greater. This experimental study of the fission kinetics of $Th^{229}+n_{th}(\sigma_f^{th}\sim 45b)$ was undertaken in order to extend the knowledge of fission kinetics to the lightest of the thermal neutron induced fissioners and in order to give an added basis upon which to construct theoretical and empirical concepts of fission.

* Operated by The University of Chicago for the U. S. Atomic Energy Commission.

[1] D. Brunton and G. Hanna, Can. J. Research **A28**, 190 (1950).

[2] J. Milton and J. Fraser, Chalk River Report PD-288 (to be published).

[3] A. B. Smith *et al.*, Phys. Rev. **106**, 779 (1957).

[4] W. E. Stein, Phys. Rev. **108**, 94 (1957).

[5] A. B. Smith *et al.*, Phys. Rev. **102**, 813 (1956).

EXPERIMENTAL ARRANGEMENT

A conventional back-to-back electron collection chamber[6] was used to measure simultaneously the ionization of each of the fragments from the binary fission of Th^{229}. This instrument's resolution was better than 1% when used to study the energy distribution of

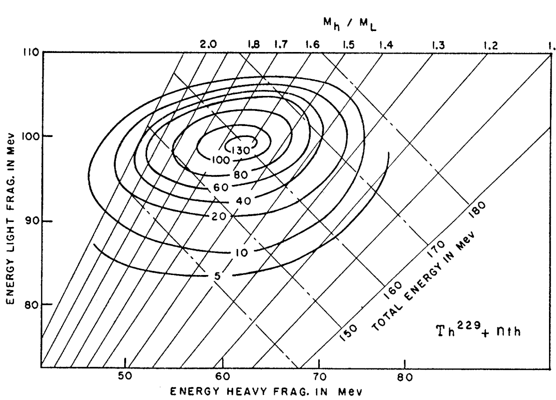

FIG. 1. Topological plot of the fission modes of $Th^{229}+n_{th}$.

[6] O. Bunemann *et al.*, Can. J. Research **A27**, 191 (1949).

TABLE I. Summary of fission fragment properties.

Fissile isotope	Z^2/A	Energy[c] of light fragment in Mev	Energy[c] of heavy fragment in Mev	Total fragment energy[c] in Mev	Mass of heavy fragment / Mass of light fragment (Kinetic measurements[e])	(Chemical measurements)	Primary heavy fragment mass	Primary light fragment mass	Reference
Th^{230b}	35.22	98	62	160±3	1.57±0.03	...	141	89	This work
U^{234b}	36.17	97[d]	66[d]	163±2	1.47±0.02	1.46	139	95	f,g
U^{236b}	35.86	98[d]	67[d]	165±2	1.46±0.02	1.45	140	96	f,h
$Pu^{240a,b}$	36.82	100[d]	72[d]	172±2	1.39±0.02	1.39	140	100	f,i
$Pu^{242a,b}$	36.51	101	73	174±3	1.38±0.02	...	140	102	j
Cf^{252b}	38.11	105.0	80	185±4	1.33±0.04	1.33	144	108	k,l,m

[a] Thermal neutron induced fission.
[b] Spontaneous fission.
[c] All ionization chamber measurements corrected for the ionization defect, see reference 4.
[d] Denotes average values. All others are most probable values.
[e] Primary fragments ratios.
[f] See reference 4.
[g] L. Glendenin *et al.*, Phys. Rev. **95**, 867 (1954).
[h] L. Glendenin *et al.*, Phys. Rev. **84**, 860 (1951).
[i] E. Steinberg and M. Freedman, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1951), Paper No. 210, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.
[j] A. B. Smith *et al.*, Phys. Rev. **106**, 779 (1957).
[k] L. Glendenin and E. Steinberg, J. Inorg. Nuclear Chem. **I**, 45 (1955).
[l] See reference 5.
[m] See reference 2.

5-Mev alpha particles. The source material consisted of isotopically pure Th^{229} obtained as a product of the alpha decay of U^{233}. The sample was prepared by subliming 0.6 μg of thorium chloride onto a thin ($\sim 2\mu g/cm^2$) organic film. The detector system was placed in a thermal neutron beam from the Argonne National Laboratory research reactor. A total of $\sim$6000 Th^{229} fission events were recorded. The energy response of the detector system was calibrated by using a U^{235} standard. The results were corrected for the fragment ionization defect as determined from velocity studies of U^{235} fission.[4]

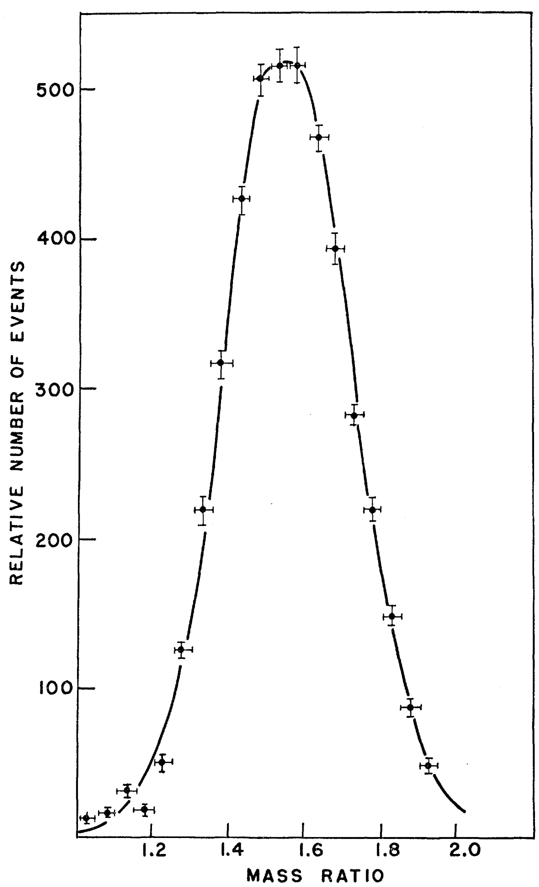

FIG. 2. Mass ratio distribution from $Th^{229}+n_{th}$ fission.

RESULTS AND CONCLUSIONS

The voltage pulse heights induced by the ionization resulting from the passage of the fission fragments through the chamber gas were recorded on "punch cards." All data processing was carried out with a large digital computer using these cards. The qualitative features of the fission of $Th^{229}+n_{th}$ are presented in topological form in Fig. 1. The process is asymmetric. This is shown quantitatively by the mass ratio distribution given in Fig. 2. The most probable mass ratio determined from this distribution is 1.57±0.03.

The total fragment kinetic energy distribution integrated over all modes is shown in Fig. 3. The average energy is 160 Mev. The full width of this distribution (at half-maximum) is 11%. When correction is made for the finite channel size shown in the figure, this width reduces to 10%. The average total fragment kinetic energy at the most probable mode is 160±3 Mev, but the distribution is narrower than that shown in Fig. 3, with a full width at half maximum of 8.5%. These widths are not corrected for the dispersion in the fragment ionization process. This ionization dispersion is a poorly understood phenomenon[7]; however, 3–5% is a reasonable estimate of the energy dispersion per fragment. Assuming this dispersion, the full width at half maximum of the total fragment kinetic energy distribution at the most probable mode is between

[7] R. B. Leachman, Phys. Rev. **87**, 444 (1952).

7.7% and 8.3%. This measured Th^{229} width tends to be narrower than that occurring at U^{235} fission[4] and is much smaller than the measured total energy width resulting from the fission of Cf^{252}.[2,5] This narrow width is verified in a qualitative way by comparing the raw data pulse-height distributions from U^{235} and Th^{229} fission. The latter distribution has a much deeper valley between the two fragment energy peaks.

The dependence of the average total fragment kinetic energy on the mass ratio is shown in Fig. 4. As symmetry

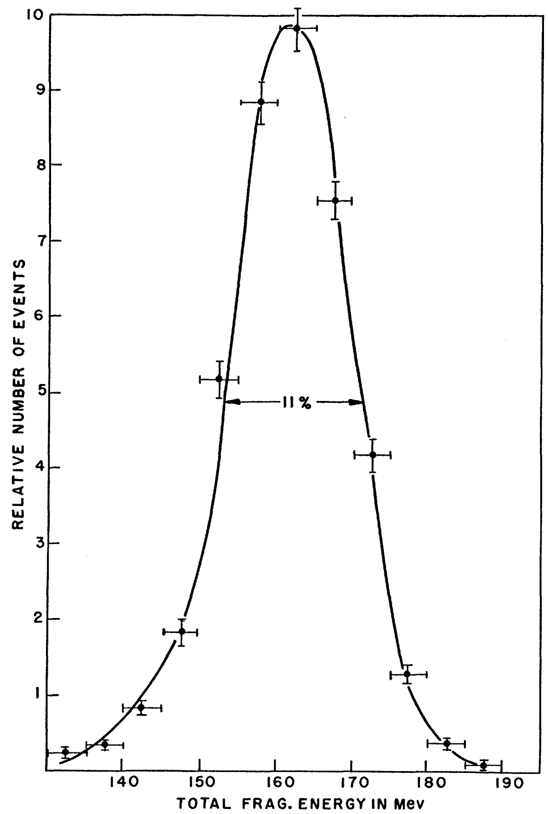

FIG. 3. Total fragment kinetic energy distribution integrated over all modes.

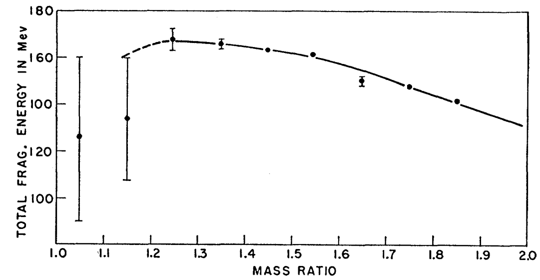

FIG. 4. Average fragment kinetic energy as a function of mass ratio.

is approached the average energy increases, up to mass ratio 1.2. This trend is in agreement with other known fission processes and with theory.[8] For mass ratios between 1.0 and 1.2 the average total kinetic energy tends to decrease. This drop, very near symmetry, is similar to that found in U^{235} fragment studies.[4] However, it must be stressed that the average kinetic energy at modes very near symmetry is not well known due to the very few events in this region.

A comparison of the properties of the more common fission processes, including the results of the present experiment, is given in Table I. From the table it is evident that Th^{229} has the lowest fragment kinetic energy and the highest degree of asymmetry. The table also gives the most probable values of the primary mass yields. It is evident that the heavy-fragment mass remains essentially constant for most fission processes while the light-fragment mass shifts to account for the change in the mass of the fissioning isotope. The narrow spread in the total fragment kinetic energy in Th^{229} fission is in agreement with theoretical predictions, and indicates that only a relatively small amount of energy is available in this fission process.

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[8] P. Fong, Phys. Rev. **102**, 434 (1956).