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Photofission of ^{232}Th with 9, 15, and 38 MeV peak bremsstrahlung*†

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The mass-yield distribution of fission products following photofission of ^{232}Th using peak bremsstrahlung energies of 9, 15, and 38 MeV were measured by γ spectrometry for 25 mass chains in the light and heavy mass wings. Fission yields for mass chains 85, 87, 88, 138, and 146 were measured for the first time for the photofission of ^{232}Th in this work. Several fractional chain yields were measured and various postulates of charge distribution were tested to correlate the experimental data. The Nethaway modified empirical Coryell method showed the best correlation with the observed charge distributions. Evidence for fine structure was observed from the 9 and 15 MeV irradiations in both the heavy and light mass wings with peaks occurring at $A = 134$ and 93, respectively. The inner portions of the mass wings both exhibited increasing splay as the irradiation energy was increased, indicating that symmetric fission was enhanced with increased energy.

NUCLEAR REACTIONS, FISSION ^{232}Th(γ,f), $E_{(\text{peak bremsstrahlung})} = 9$, 15, and 38 MeV; measured mass-yield distribution, 25 mass chains, heavy, light mass wings by γ spectrometry; measured several fractional yields, tested several charge distribution postulates, Ge(Li) detectors, 3.34 keV at 1.33 MeV, 2.3 keV at 1.33 MeV.

I. INTRODUCTION

Photofission mass-yield distributions have been reported by many authors,[1-14] and discussions of these results for ^{232}Th, ^{238}U, and other nuclei can be found in papers by Lazareva and Nikitina,[15] Hyde,[16] Vandenbosch and Huizenga,[17] and more recently Hoffman and Hoffman,[18] and Aumann.[19] Conspicuously absent are comprehensive mass yield investigations of ^{232}Th photofission. Moreover, independent yield or fractional independent yield data for photofission systems in general are particularly sparse when compared to those available for neutron fission.

Investigation of ^{232}Th photofission appeared promising because of the calculated high fission barrier.[20] Bohr had earlier suggested that such a high barrier might lead to fine structure in the mass yield distribution for fission induced by low-energy photons.[21] Such fine structure should be diminished at higher photoexcitation energies where the fission barrier exerts less influence.

The primary purpose of this investigation has been to establish the mass yield distribution for ^{232}Th photofission from peak bremsstrahlung energies just above threshold to about 40 MeV. Another objective has been to obtain fractional independent yield data for ^{232}Th photofission and to use this data along with that in the literature to choose a calculational method for determining fractional independent yields (FIY's).

II. EXPERIMENTAL

Pure ^{232}Th as a 1.3 cm diameter disk with mass 0.38 g was wrapped in nuclear pure aluminum and irradiated with a bremsstrahlung beam produced by 9, 15, or 38 MeV electrons impinging on a thin, water-cooled platinum target. The irradiation conditions are listed in Table I.

High resolution γ spectrometry without chemical separations was used to identify fission products and determine fission yields. The γ spectrometry data were collected in an appropriate prearranged time sequence beginning 10 min after irradiation with as many as 200 spectra recorded per irradiation. These spectra were collected by a Nuclear Data 3300, 4096-channel analyzer with an on-line computer and associated equipment. The detector used for the irradiations at 15 MeV and the first irradiation at 9 MeV was a Nuclear Diode detector with a 3.34 keV resolution for 1.33 MeV ^{60}Co and 5% efficiency. The detector used for the second and third irradiations at 9 MeV and the irradiation at 38 MeV was an Ortec detector with a 2.3 keV resolution for 1.33 MeV ^{60}Co and a 16.1% efficiency.

TABLE I. Experimental irradiation conditions.

Irradiation number	Max bremsstrahlung energy (MeV)	Length of irradiation	Pulse rate (sec^{-1})	Beam current (mA)
1	9	10 min	10	240
2	9	2 h	10	240
3	9	20 min	120	375
4	15	10 min	10	240
5	15	2 h	10	240
6	38	40 sec	10	580

The γ spectrometry data were reduced by the computer code SAMPO, a general-purpose semiconductor detector spectral analysis code written by Routti and Prussin[22] which had been adapted to the Univac 1108 computer. Other programs to calculate the correction factor for detector efficiency versus energy, to determine a foil self-shielding correction factor versus energy, and to search a γ ray library were also used.

No *a priori* γ ray assignments were made. Fission products were identified by determining the half-lives associated with the various γ rays. It was felt that by such a procedure interfering γ activities and fission products which might otherwise have been overlooked could be found.

Once reduced, all spectra from a given irradiation were combined and then sorted by another program for like-energy photopeaks. After the background was subtracted the sets of like-energy photopeaks were analyzed by a program which calculated the respective half-lives.

From a knowledge of the absolute activity at the end of irradiation, the total number of atoms of an isotope produced during the irradiation was determined by applying a correction for the decay of the isotope during irradiation:

$$A_{\text{Total}} = \frac{A_i T}{(1 - e^{-\lambda_A T})} ,$$

where A_{Total} is the total number of atoms of species A, A_i is the activity of A at end of irradiation, T is the length of irradiation, and λ_A is the decay constant of nuclide A. The absolute yield of ^{140}Ba was not determined directly. It was assigned a relative value of 7.81%, the same as that determined for the fast neutron fission of ^{232}Th.[23] This assignment was considered satisfactory for three reasons: (1) no direct yield determinations have been made for ^{140}Ba from ^{232}Th photofission, (2) Chattopadhyay *et al.*[11] felt their reported value to be low, and (3) percent yield in this mass region is considered to be insensitive to A.[18] All relative yields were determined by $Y_i = (Y_{140}/N_{140})A_{\text{Total}}$, where Y_{140} is 7.81% and N_{140} is the number of atoms of ^{140}Ba. Mass yields were corrected to chain yields from independent yields calculated by the Nethaway method[24] with $\sigma = 0.56$.

In the cases where fractional independent yields (FIY's) and fractional cumulative yields (FCY's) were determined the following method was applied: The activities of both the parent and its daughter in a given mass chain were measured, and the FCY of the daughter was assumed to be equal to one. The FCY of the parent and the FIY of the daughter were then calculated by using equations which accounted for growth and decay during and after irradiation.[25]

III. EXPERIMENTAL ERRORS

During irradiation both the energy of electrons and the beam current could vary, but by careful tuning of the Linac during irradiation these errors were minimized. Fluctuations were about ± 1 MeV in the peak energies and ± 5% in the beam currents.

Energy fluctuation errors in the 9 and 38 MeV irradiations should have caused negligible effects in yields. The 9 ± 1 MeV range would cause fissions primarily through a 6 MeV resonance, while the 38 ± 1 MeV range is well above all resonances. Even though the 15 ± 1 MeV peak bremsstrahlung is on the edge of the 14 MeV dipole resonance, the peak intensity is comparatively small, and the yields observed for this irradiation should mainl reflect the fission from below 14 MeV.

Fluctuations in beam intensity would show significant effects only upon the measured yields of nuclides with half-lives short with respect to the length of the irradiation. Thus, for the 40 sec irradiation any beam fluctuations would have a negligible effect, since all measured half-lives were 5 min or greater. For irradiations of duration longer than measured half-lives, small errors in yields for nuclides with those half-lives could have resulted.

Another source of error could be fissions induced by secondary neutrons from the bremsstrahlung target and other sources. However, neutron dosimeters showed that neutron intensities were negligibly small for all of the irradiations. A search was made for the neutron-capture product ^{233}Th, but it was not found, except possibly after one of the 15 MeV irradiations where trace amounts were suspected. Under similar irradiation conditions, Gevaert *et al.*[9] gave an upper limit of 0.5% contribution to the yields from neutron-induced fissions for irradiations of 1–3 h durations.

During irradiation some fission fragments recoil out of the ^{232}Th foil. However, only negligible amounts of fission products were observed to recoil into nuclear-pure aluminum catcher foils.

For most of the mass chains, the yields were based on photopeak activity which had been measured over several half-lives. Chain yields were determined from as many members of the chain as gave measurable activities. Where possible, activities were calculated from more than one γ ray photopeak from a particular nuclide. If there were disagreements in the activities calculated on the basis of these γ rays, the yield obtained from the most intense γ ray photopeak was favored. For consistency the calculations were based on the fractional γ ray abundances and half-lives given in Ref. 26 except ^{93}Sr[27] and ^{140}Ba.[28]

A problem sometimes encountered with the fitting routine of SAMPO[22] was that the fit to a photopeak did not have a linear continuum. If such a photopeak was to be used for a calculation of mass yield, the photopeak intensity was determined by graphical integration. Because of possible errors involved in fitting multiplets, they were not used for mass yield calculations, but they were used to determine half-lives and identify fission products. The use of multiplets was avoided by studying all the γ rays and choosing the most isolated and best fitted photopeak for a particular nuclide.

Counting detector efficiency and self-shielding errors were treated in the usual manner.[25] Errors in fractional γ ray abundances and half-lives have been estimated by noting the magnitude of the changes in these values as new values have become available from the literature. One additional error would be reflected in the mass chain yields as the result of making these yields relative to 7.81% assigned for ^{140}Ba. The estimated errors given in this work for both the mass yields and the fractional independent or fractional cumulative yields included contributions from counting statistics and the errors cited above.

IV. RESULTS AND DISCUSSION

Fractional yields

Photofission independent yield data for any nuclide is sparse. Both ^{232}Th and ^{238}U are even-even heavy nuclides not greatly different in mass. Since charge distribution probabilities for their respective photofissions should be quite similar, previous photofission data for ^{238}U and ^{232}Th along with our data for the latter would provide data to evaluate various calculational methods for estimating unknown fractional independent yields (FIY's) and testing measured ones.

Three methods were tested for their consistency with experimental data. The most probable charge (Z_p) was calculated in all three methods. (1) The Pappas modified equal-charge-displacement (ECD) hypothesis[29] states that the most probable charges for a fission fragment and its complement are equal units away from β stability except as modified to account for shell effects. (2) The deviation from the unchanged-charge-distribution (UCD) hypothesis[30] assumes that the compound nucleus fissions rapidly and charge polarization does not take place, with Z_p corrected by approximately -0.45 for heavy fragments. (3) The Coryell[31,32] and Nethaway[24] empirical approaches are both least-squares techniques to correlate all fractional chain yields using thermal neutron fission of ^{235}U as a reference. An even-Z enhancement and odd-Z depression by a factor of 1.20 was used for all three methods for determining Z_p empirically. The Pappas modified ECD hypothesis has generally been used for low-energy neutron or proton fission of uranium and thorium. Examples include low-energy neutron-induced fission of ^{233}U,[33] ^{235}U,[34] 14.7 MeV neutron fission of ^{238}U,[35] low and intermediate fission of ^{232}Th,[36,37] and the proton-induced fission of ^{232}Th.[34,38] Using the deviation from UCD, close agreement between calculated and experimental values has been obtained for the thermal neutron fission of ^{235}U.[39] Wolfsberg[40,41] has also applied the deviation from UCD to low-energy fission induced by thermal neutrons in ^{233}U, ^{235}U, and ^{239}Pu; fission spectrum neutrons in ^{235}U, ^{238}U, and ^{239}Pu; and 14.7 MeV neutrons in ^{235}U, ^{238}U, and ^{239}Pu. Where experimental results were available, the agreement with the calculated values was generally good. The Nethaway method has been applied successfully to many nuclei at different excitation energies.[24]

Table II lists the experimental values for FIY or FCY for ^{232}Th photofission determined in this work as compared to the Nethaway calculated values. The FIY and FCY values from this work, Cunninghame *et al.*,[42] Chattopadhyay *et al.*,[11] and Parsons and Sharma[43] whether for ^{238}U or ^{232}Th were corrected by the even-Z enhancement, odd-Z depression factor of 1.20 to determine Z_p empirical values. Tables III and IV compare Z_p (Emp) with theoretical Z_p values from the photofission at 14 MeV excitation of ^{238}U and ^{232}Th, respectively.

TABLE II. Experimental FCY and FIY for ^{232}Th photofission compared to Nethaway calculated method.

	Experimental		Nethaway calculated	
Nuclide	FCY	FIY	FCY	FIY
^{91}Sr	≳0.99		0.99	
^{91}Y^m		0.0		0.0003
^{92}Sr	0.98 ±0.01		0.996	
^{92}Y		0.02 ±0.01		0.003
^{93}Sr	0.91 ±0.06		0.98	
^{93}Y		0.09 ±0.06		0.021
^{132}Te	≳0.99		0.989	
^{132}I		0.0		0.011
^{134}Te	0.79 ±0.06		0.78	
^{134}I		0.21 ±0.06		0.212
^{135}I	0.905±0.025		0.933	
^{135}Xe		0.095±0.025		0.067
^{138}Xe	0.80 ±0.07		0.90	
^{138}Cs		0.20 ±0.07		0.093
^{146}Ce	0.982±0.009		0.996	
^{146}Pr		0.018±0.009		0.004

In comparing the different methods with experimental values the best overall correlation for both ^{238}U and ^{232}Th was obtained with the Nethaway method. The better agreement of the empirical approach is perhaps not surprising, as it was developed from many nuclei at different excitation energies.

When formulated, the deviation from UCD was applied to thermal neutron fission of ^{235}U. However, at that time its authors indicated it might also be useful for other low-energy neutron-induced fission processes, especially other uranium fissioning systems.[44] The method has not proved entirely satisfactory for the fission of plutonium,[40] and there has been no claim that it should apply to the neutron-induced fission of ^{232}Th, much less to the photofission of either ^{238}U or ^{232}Th. The deviation from UCD appears to be on a firmer theoretical base than the other methods,[45] and as the number of neutrons emitted as a function of fragment mass becomes better known it should become more generally applicable than it is now.

TABLE III. Comparison of Z_p(Emp) with theoretical Z_p values for the photofission of ^{238}U (14 MeV excitation).

A	Z_p(Emp)	$Z_p(1)$[a]	$Z_p(2)$[b]	$Z_p(3)$[c]
82	32.68[d]	32.56	32.44	32.56
96	38.30[d]	38.28	38.16	38.29
126	49.91[e]	49.03	48.70	48.93
128	49.85[e]	49.68	49.35	49.61
131	50.65[f]	50.82	50.49	50.37
132	51.39,[e] 50.12[f]	51.23	50.90	50.80
133	51.77,[e] 51.54[f]	51.67	51.34	51.27
134	52.09[e]	52.14	51.81	51.75
135	52.70[e]	52.58	52.25	52.21
136	48.90,[d] 53.19[e]	53.00	52.67	52.63
140	54.80[d]	54.61	54.28	54.24

[a] $Z_p(1)$, Nethaway.

[b] $Z_p(2)$, Coryell.

[c] $Z_p(3)$, deviation from UCD.

[d] Cunninghame *et al.* (Ref. 42).

[e] Chattopadhyay *et al.* (Ref. 11).

[f] Parsons and Sharma (Ref. 43).

TABLE IV. Comparison of Z_p(Emp) with theoretical Z_p values for the photofission of ^{232}Th (14 MeV excitation).

A	Z_p(Emp)	$Z_p(1)$[a]	$Z_p(2)$[b]	$Z_p(3)$[c]	$Z_p(4)$[d]
82	32.41[e]	31.81	32.88	32.58	32.59
92	37.39[f]	36.62	36.99	36.69	36.68
93	37.81[f]	37.09	37.40	37.10	37.09
96	38.09[e]	38.26	38.60	38.30	38.28
131	50.72[g]	50.66	50.85	50.63	50.51
132	51.25[g]	51.00	51.26	50.04	50.94
133	51.79[g]	51.74	51.70	51.48	51.39
134	51.99[f]	51.92	52.17	51.95	51.86
135	52.82[f]	52.25	52.61	52.39	52.30
136	52.76[e]	52.91	53.02	52.81	52.72
138	54.11[f]	53.84	53.84	53.62	53.52
146	57.21[f]	57.72	57.05	56.83	56.72

[a] $Z_p(1)$, ECD method.

[b] $Z_p(2)$, Nethaway.

[c] $Z_p(3)$, Coryell.

[d] $Z_p(4)$, deviation from UCD.

[e] Cunninghame *et al.* (Ref. 42).

[f] This work.

[g] Parsons and Sharma (Ref. 43).

The experimental fractional independent yields obtained in this work, even though generally in line with those from other investigations, have rather large uncertainties since they were obtained by finding the difference between two large numbers. Also, as was previously mentioned, slight fluctuations in beam current can cause large errors in measured activities when half-lives are short compared to irradiation times. The abnormally high 0.09% yield of ^{93}Y which we observed may be due to experimental error caused by the relative shortness of the 7.3 min half-life of its parent compared to the 20 min irradiation time coupled with beam fluctuations. Even with such uncertainties the FIY (FCY) data do set approximate limits for FIY values and as such are useful in evaluating methods for predicting FIY's. Such predictions are valuable for designing new experiments. As explained above, the Nethaway method appears to be the best method now available for predicting FIY values for the photofission of ^{238}U and ^{232}Th.

Chain yields

Fifty-six fission products and 27 mass chains were identified from the irradiations at 9, 15, and 38 MeV. The observed mass chain yields are reported in Table V according to peak incident photon energy. Fission yields for mass chains 85, 87, 88, 138, and 146 are reported here for the first time for the photofission of ^{232}Th. These mass yields were all from nuclides which had relatively short half-lives, demonstrating one advantage of this technique over the generally more time-consuming radiochemical separation techniques. Also, from one short irradiation alone the yields of 25 mass chains were measured simultaneously, thereby eliminating the calibration errors associated with radiochemical techniques. The latter generally require multiple irradiations since the yields of only a few short-lived products can be determined from one irradiation.

The chain yields from mass chains 105 and 115 were not evaluated because of the poor statistics obtained for the γ ray photopeaks of the isobars involved. For the other 25 mass chains the yields were based on photopeak activities which had been measured over several half-lives, generally from several members of the chain. Where possible, more than one γ ray photopeak from a particular nuclide was measured.

The photofission cross section becomes significant at the threshold (5.4 MeV), after which it rises with increasing energy to a maximum of approximately 50 μb at 14 MeV and then drops to essentially zero at energies greater than 25 MeV.[16] In the high energy region (80–250 MeV) the cross section again increases to approximately 50 μb.[15]

TABLE V. Photofission yields of ^{232}Th determined in present work normalized to ^{140}Ba.

Mass no.	9 MeV	15 MeV	38 MeV
83	1.52 ± 0.16	2.15 ± 0.18	2.24 ± 0.16
85	6.75 ± 0.75	5.75 ± 0.53	5.50 ± 0.50
87	7.87 ± 0.65	7.43 ± 0.55	7.20 ± 0.53
88	6.09 ± 0.55	6.00 ± 0.49	6.16 ± 0.48
89	7.81 ± 0.71	8.25 ± 0.85	7.92 ± 0.80
91	6.75 ± 0.32	6.61 ± 0.31	8.37 ± 0.40
92	5.99 ± 0.39	5.88 ± 0.48	7.33 ± 0.60
93	7.21 ± 0.65	7.03 ± 0.60	8.02 ± 0.53
94	5.42 ± 0.54		6.10 ± 0.88
95			5.39 ± 0.60
97	2.90 ± 0.14	3.26 ± 0.18	3.88 ± 0.21
99	1.09 ± 0.10	1.73 ± 0.09	2.40 ± 0.13
129			1.04 ± 0.16
131	0.95 ± 0.08	2.20 ± 0.20	2.74 ± 0.18
132	1.69 ± 0.10	3.20 ± 0.18	3.71 ± 0.21
133	3.22 ± 0.18	4.53 ± 0.25	5.61 ± 0.37
134	7.90 ± 0.72	6.75 ± 0.61	6.46 ± 0.38
135	5.48 ± 0.49	6.08 ± 0.55	6.70 ± 0.55
138	6.09 ± 0.50	6.00 ± 0.54	7.16 ± 0.76
139	6.62 ± 0.71	6.70 ± 0.77	6.75 ± 0.70
140	7.81	7.81	7.81
141	9.06 ± 0.51	8.26 ± 0.61	8.40 ± 0.62
142	7.87 ± 0.71	7.20 ± 0.71	6.86 ± 0.57
143	8.53 ± 0.41	7.89 ± 0.37	7.30 ± 0.42
146	3.57 ± 0.41		2.80 ± 0.40

The same general trends in the cross section noted above for ^{232}Th also apply to ^{238}U with the giant dipole resonance peaking at about 14 MeV, but with the latter peak several times larger than that for ^{232}Th.[16] For ^{238}U photofission at 22, 24, and 26 MeV bremsstrahlung peak energies, it has been demonstrated that most of the photofission occurs at the maximum cross section near 14 MeV, irrespective of the maximum bremsstrahlung energies.[5]

The results of the investigation of photofission of ^{232}Th at peak bremsstrahlung energies of 25, 30, 35, and 40 MeV by Chattopadhyay *et al.*[11] also support the fact that most of the photofissions occur at the giant dipole resonance (14 MeV). Most mass yields which they reported were constant within the specified error limits irrespective of the irradiation energy. The few yields which showed some trends of either increasing or decreasing with greater incident energy between 25 and 40 MeV did not change in value over 25%.

Because of the low photofission cross section above 25 MeV one can justifiably compare mass yields derived from irradiations with energies above about 25 MeV peak bremsstrahlung. Such a comparison is made in Table VI where the yields determined in this work at 38 MeV are compared

TABLE VI. Comparison of ^{232}Th photofission yields for peak bremsstrahlung energies greater than 14 MeV with all yields normalized to ^{140}Ba.

Mass chain	Present work 38 MeV	Chattopadhyay *et al.*[a] 40 MeV	Hiller *et al.*[b] 69 MeV
83	2.24 ± 0.16		2.23 ± 0.18
85	5.50 ± 0.50		
87	7.20 ± 0.53		
88	6.16 ± 0.48		
89	7.92 ± 0.50		7.92 ± 0.12
91	8.37 ± 0.40	8.47 ± 0.68	6.74 ± 0.12
92	7.33 ± 0.60	7.42 ± 0.59	
93	8.02 ± 0.53	8.18 ± 0.65	
94	6.10 ± 0.58		
95	5.39 ± 0.60	5.50 ± 0.44	
97	3.88 ± 0.21	4.34 ± 0.35	
99	2.40 ± 0.13	1.90 ± 0.15	2.19 ± 0.12
129	1.40 ± 0.16	0.732 ± 0.06	
131	2.74 ± 0.18	2.49 ± 0.20	
132	3.71 ± 0.21	3.98 ± 0.32	
133	5.61 ± 0.37	5.07 ± 0.40	
134	6.46 ± 0.38	4.61 ± 0.37	
135	6.70 ± 0.55	3.95 ± 0.32	
138	7.16 ± 0.76		
139	6.75 ± 0.70	7.05 ± 0.56	
140	7.81	7.81	7.81
141	8.40 ± 0.62	8.94 ± 0.71	8.04 ± 0.59
142	6.86 ± 0.57	7.66 ± 0.61	
143	7.30 ± 0.42	7.20 ± 0.58	
146	2.80 ± 0.40		5.74 ± 0.59
147		2.62 ± 0.21	

[a] Reference 11. [b] Reference 8.

to those of Chattopadhyay *et al.*[11] at 40 MeV and Hiller and Martin[8] at 69 MeV. Chattopadhyay *et al.*[11] estimated that for their work the errors were less than 8% for each of the chains. These estimates are given in Table VI. For the error limits given in Table VI the agreement is excellent except for mass chains 133, 134, and 135.

For bremsstrahlung irradiations at energies lower than around 25 MeV the mass yields are more sensitive to peak bremsstrahlung energy than they are at energies greater than that value. There are small peaks in the ^{232}Th cross-section curve at 6 and 11 MeV.[16,46] At a peak bremsstrahlung energy of 9 MeV essentially all of the photofissions occur at the cross-section peak of 6 MeV, while at a peak energy of 15 MeV most occur at the 6 and 11 MeV peaks with a very small contribution from the 15 MeV peak. Thus in the range below 25 MeV one must be careful to compare only those irradiations with similar peak energies.

Accordingly, the mass yields at 9 MeV are compared to those reported by Zysin, Lbov, and Sel'chenkov[10] at 10 MeV in Table VII. In every case where mass chains were measured at both energies, the results agree within the error limits given. There are no literature values with which to directly compare the 15 MeV irradiation data whose values are listed in Table V.

The fission yield curves versus mass number for 9, 15, and 38 MeV are shown in Figs. 1, 2, and 3, respectively. The dominant feature of these curves is the asymmetric mass distribution of the products.

A characteristic trend of photofission mass yield curves has been that the valley (trough) fills in and the wings splay out as the photon energy increases. Such behavior is in line with the general trend that low and intermediate energy fission mass yield distributions show an increasing contribution from symmetric products as irradiation energy is increased.[18] The widening of the mass wings with increasing photon energy for ^{232}Th can be seen in Figs. 4 and 5, where the heavy and light mass wing yields, respectively, are plotted for 9, 15, and 38 MeV peak energies.

An apparent peak at $A = 134$ is seen in Fig. 4.

TABLE VII. Comparison of ^{232}Th photofission yields for low energy bremsstrahlung with all yields normalized to ^{140}Ba.

Mass chain	This work 9 MeV	Zysin (141) 10 MeV
83	1.52 ± 0.16	2.00 ± 0.49
85	6.75 ± 0.75	
87	7.87 ± 0.65	
88	6.09 ± 0.55	
89	7.81 ± 0.71	
91	6.75 ± 0.32	6.36 ± 1.01
92	5.99 ± 0.39	
93	7.21 ± 0.65	
94	5.42 ± 0.54	
97	2.90 ± 0.14	2.56 ± 0.57
99	1.09 ± 0.10	1.23 ± 0.22
113		0.074 ± 0.018
115		0.036 ± 0.009
117		0.041 ± 0.012
129		0.558 ± 0.28
131	0.95 ± 0.08	
132	1.69 ± 0.10	
133	3.22 ± 0.18	4.79 ± 1.89
134	7.90 ± 0.72	
135	5.48 ± 0.49	
138	6.09 ± 0.50	
139	6.62 ± 0.71	5.58 ± 0.84
140	7.81	7.81
141	9.06 ± 0.51	
142	7.87 ± 0.71	
143	8.53 ± 0.41	10.60 ±[a]
146	3.57 ± 0.41	

[a] Error not given.

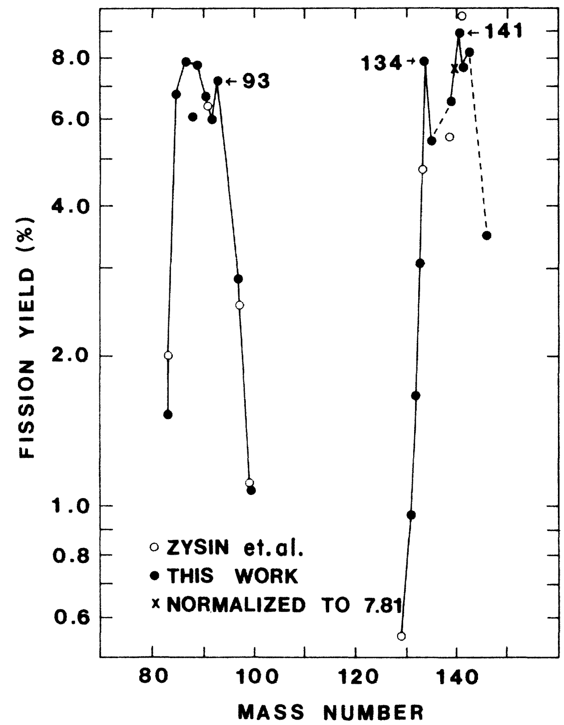

FIG. 1. Photofission of ^{232}Th with 9 MeV bremsstrahlung.

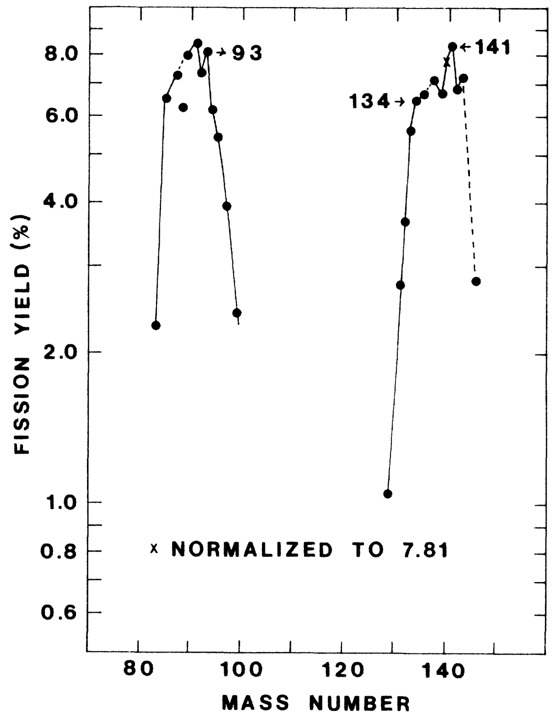

FIG. 3. Photofission of ^{232}Th with 38 MeV bremsstrahlung.

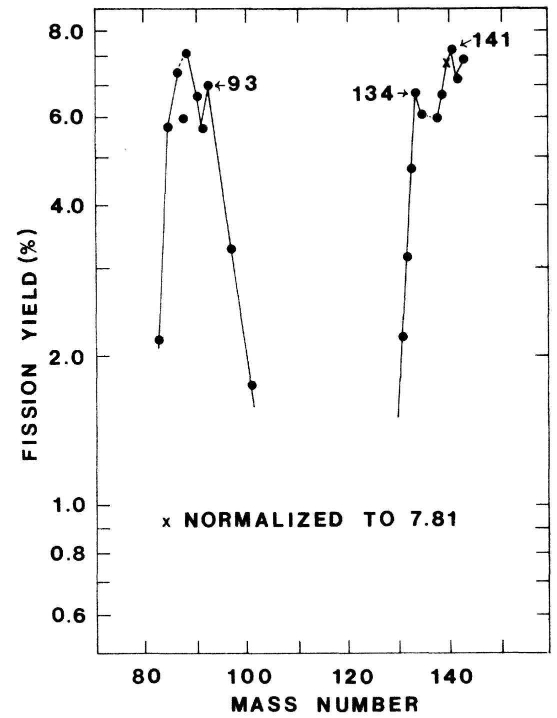

FIG. 2. Photofission of ^{232}Th with 15 MeV bremsstrahlung.

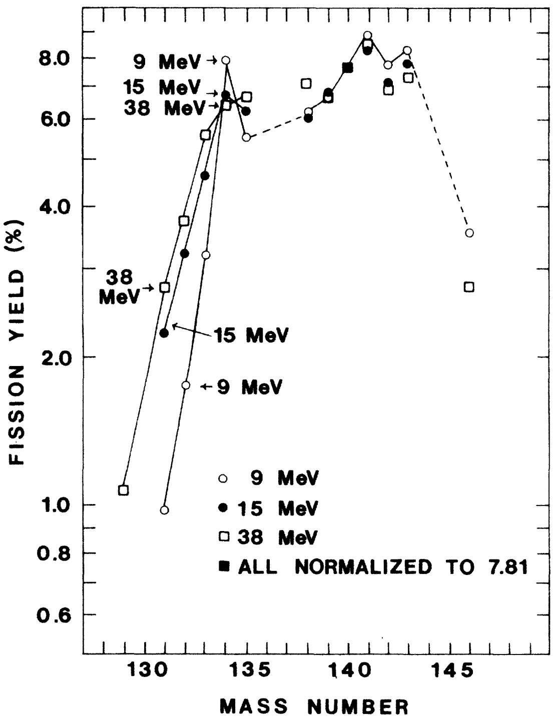

FIG. 4. Photofission of ^{232}Th with 9, 15, and 38 MeV bremsstrahlung (heavy mass wing).

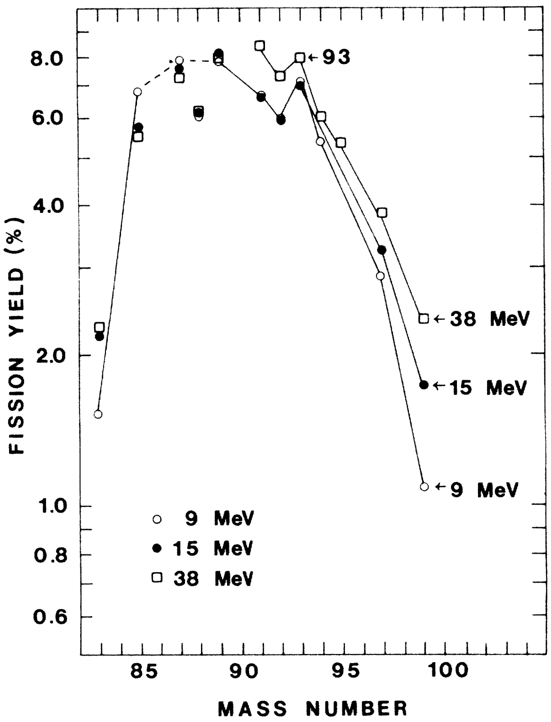

FIG. 5. Photofission of ^{232}Th with 9, 15, and 38 MeV bremsstrahlung (light mass wing).

The peak is especially pronounced for the 9 MeV irradiation, is less noticeable at 15 MeV, and is essentially obscured at 38 MeV. The smoothing-out effect at high energies appears related to an enhancement of the 135 mass chain at the expense of the 134 mass chain.

Such fine structure fluctuations from a generally smooth mass curve have also been observed for other fissioning nuclei.[6,39,47-56] The peak at $A = 134$ has usually been found to be small with some exceptions being the thermal-neutron fission of ^{235}U, ^{239}Pu, and ^{241}Pu.[57]

As early as 1956 Bohr[21] suggested that at low excitation energies most of the energy would be used as deformation energy during the passage from the initially excited nucleus to the saddle point, thereby limiting fission to a small number of channels. At these low excitation energies the excess energy above the deformation energy would very likely be insufficient to break nucleon pairs, and the formation of fragments lying near closed shells would be favored. At higher excitation energies, when the potential energy requirement of the deformation at the saddle point removed only part of the initial energy of excitation, many alternate levels would become available as fission channels, and there would be enough excess energy to break nucleon pairs.

The behavior of the peak at $A = 134$ (see Fig. 4) appears to support the Bohr hypothesis. At 9 MeV peak bremsstrahlung, at which the most probable energy of excitation is around 6 MeV, the 134 peak is well defined, at 15 MeV it is much smaller, and at 38 MeV it has all but disappeared.

In this work a slight increase in fission yields was noted from $A = 133$ to 135 for the 38 MeV irradiation, but Chattopadhyay *et al.*,[11] for a 40 MeV irradiation, observed a decrease in yields over the same range (see Table VI). In the present investigation special care was taken in determining yields for the 134 and 135 mass chains. For the 134 chain six γ rays from both ^{134}Te and ^{134}I were measured over several half-lives and then each was used to calculate the yield. The same yield was obtained for all the γ ray photopeaks within the error limits shown in Table VI. For the 135 chain seven γ rays were studied to determine the mass yields. These values were also consistent within the error limits reported in Table VI. In contrast, Chattopadhyay *et al.*[11] based their value for mass 135 on only one γ photopeak compared to the six used here. Their values for mass 134 from both radiochemistry and pure γ spectra are in apparent internal agreement. γ ray abundances used for masses 134 and 135 for both their investigation and ours agree to within 4%. At present, no simple explanation for the observed discrepancies is apparent.

Chattopadhyay *et al.*[11] also reported photofission mass yield distribution studies for ^{238}U with peak bremsstrahlung energies of 25, 30, 35, and 40 MeV in which the values at $A = 135$ were again low with respect to the rest of the mass yield curve. These low values are in apparent disagreement with similar photofission studies of ^{238}U obtained by Swindle *et al.*[5] at 22, 24, and 26 MeV peak bremsstrahlung and Richter and Coryell[58] at 16 MeV bremsstrahlung.

Chattopadhyay *et al.*[11] compared their low yield at $A = 135$ for ^{238}U photofission with that obtained by Meason and Kuroda[59] in a ^{238}U photofission study using 17.5 MeV monoenergetic γ rays. Meason and Kuroda[59] had also reported a low yield at $A = 135$ but, in addition, had observed a pronounced fine structure at $A = 132$. Since Chattopadhyay *et al.*[11] did not observe fine structure at $A = 132$, the overall comparison is open to question. The differences in results probably arise from the use of 17.5 MeV monoenergetic photons in one case and bremsstrahlung in the other.

A peak at $A = 134$ similar to the one seen in this work has been observed for fission-spectrum neutron fission of ^{232}Th[57] and the 3.0 MeV fission of ^{238}U.[60] These are further evidence that the peak in this work at mass 134 is more consistent with general fission trends than are the results observed by Chattopadhyay *et al.*[11]

The light wing mass yields are plotted in Fig. 5. Evident from the graph in the mass region $A = 91$–94 is the peak located at $A = 93$ with a dip at $A = 92$. As the maximum bremsstrahlung energy is increased, the fine structure remains but is slightly diminished at 38 MeV. The dip in the curve at $A = 92$ is similar to that observed for the ^{232}Th and ^{238}U photofission of Chattopadhyay *et al.*,[11] 16 MeV photofission of ^{238}U of Richter and Coryell,[58] and the fission-spectrum neutron induced fission of ^{232}Th of Nethaway and Barton.[23] One explanation for the peak at $A = 93$ could be the preferred formation of primary fragments with even nuclear charges.[39,47,48] An unexplained low yield at $A = 88$ can also be noted.

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