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Fission Fragment Angular Distributions
for ^{230}Th , ^{232}Th , ^{231}Pa , and ^{239}Pu



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D. W. Muir

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FISSION FRAGMENT ANGULAR DISTRIBUTIONS FOR ^{230}Th , ^{232}Th , ^{231}Pa , and ^{239}Pu

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ABSTRACT

Recently published experimental data on the angular distribution of fragments from the neutron-induced fission of ^{230}Th , ^{232}Th , ^{231}Pa , and ^{239}Pu are fit with a power series in $\cos\theta$. The data, fitting coefficients, and values calculated at 15 and 80° are presented at neutron energies up to 3.0 MeV.

I. INTRODUCTION

The fission cross sections of ^{230}Th , ^{232}Th , and ^{231}Pa were recently measured¹ relative to ^{239}Pu , over an energy range from 0.1 to 3.0 MeV, using an underground nuclear detonation as a pulsed neutron source. Fission fragments were detected at laboratory angles, θ , of 100 and 165° relative to the neutron beam direction. The purpose of this report is to discuss the methods and the sources of angular distribution data used in Ref. 1 to construct the ratio

$$R(\theta) = \frac{4\pi \frac{d\sigma}{d\Omega}}{\int d\Omega \frac{d\sigma}{d\Omega}} \quad (1)$$

This ratio, which ranges from 0.56 to 2.16 in cases of interest here, was needed in order to convert the differential data into angle-integrated fission cross sections.

II. ANGULAR DISTRIBUTIONS

This differential-to-integral conversion has become feasible with the recent availability of a large body of fragment angular distribution data,²⁻¹¹ most of which was obtained with dielectric track detectors. Usually, the angular distribution, $W(\theta)$, is measured only on a relative basis. That is,

$$W(\theta) = k \frac{d\sigma}{d\Omega} \quad (2)$$

where the factor k is independent of θ , but otherwise not specified. Since we are interested only in a ratio, Eq. (1), the absolute normalization of the distribution is unimportant.

For a particular nuclide and at a particular energy, we fit the experimental data with a power series in $\cos\theta$,

$$W(\theta) \simeq \sum_n a_{2n} \cos^{2n}\theta \quad (3)$$

Only the even powers in $\cos\theta$ are included, since the fragment distributions are symmetric about a laboratory angle of 90°, except for small kinematic effects. For the same reason we shall speak of cross sections at 15 and 80° rather than the actual back angles used in Ref. 1.

It will be convenient to normalize the distributions from the various sources in a consistent fashion. To do this, we divide both sides of Eq. (3) by a_0 .

$$N(\theta) = \frac{1}{a_0} W(\theta) = 1 + \alpha_2 \cos^2\theta + \alpha_4 \cos^4\theta + \dots \quad (4)$$

where

$$\alpha_{2n} = \frac{a_{2n}}{a_0} \quad (5)$$

Thus, $N(\theta)$ is an experimental fragment angular distribution, expressed as the ratio of the number of

fragments per steradian to the number predicted at 90° by our fit to the distribution. We can now write the ratio, $R(\theta)$, in terms of the coefficients α_{2n} . From Eqs. (1), (2), (3), and (5), we have

$$R(\theta) = \frac{1 + \alpha_2 \cos^2 \theta + \alpha_4 \cos^4 \theta + \dots}{1 + \alpha_2/3 + \alpha_4/5 + \dots} \quad (6)$$

III. DETAILS OF THE FITTING

The criterion used to fit the experimental data is that

$$\Delta^2 = \sum_i \left[W(\theta_i) - \sum_n a_{2n} \cos^{2n} \theta_i \right]^2$$

be a minimum, with respect to the variables a_{2n} . The condition

$$\frac{\partial \Delta^2}{\partial a_{2n'}} = 0 \quad (n' = 0, \dots, n_{\max})$$

gives $(n_{\max} + 1)$ equations of the form

$$\sum_{n=0}^{n_{\max}} a_{2n} \left[\sum_i (\cos \theta_i)^{2n+2n'} \right] = \left[\sum_i W(\theta_i) \cos^{2n'} \theta_i \right] \quad (7)$$

where n_{\max} varies from nuclide to nuclide, depending on the number of terms required to give a reasonable fit to the data. The distribution for

^{239}Pu is quite smooth, so $n_{\max} = 1$ is sufficient.

The increased anisotropy in nuclides ^{230}Th and ^{231}Pa requires $n_{\max} = 2$. In fitting their data on ^{232}Th with Legendre polynomials, Ermagambetov and Smirenkin² found it necessary to go up to $P_6(\cos \theta)$, which would be equivalent in our treatment to taking $n_{\max} = 3$. The final step, of course, is to solve Eq. (7) for the $(n_{\max} + 1)$ coefficients a_{2n} . We now present the experimental data and the results of our analysis for the nuclides of interest.

IV. DISTRIBUTION FOR ^{230}Th

The distribution of fragments from ^{230}Th has recently been measured from 0.682 to 0.750 MeV with high energy resolution by Yuen et al.³ Their data, normalized as shown in Eq. (4), and their quoted standard error are presented in Table I, below, in the numerator of each entry. For purposes of comparison, our three-parameter fit to the angular distribution is given in the denominator. The actual values of the fitting parameters and the calculated angular correction factor, $R(\theta)$, will be presented later in this report.

Since the normalization factor, $\frac{1}{a_0}$, is based on a large number of data points, the uncertainty in it will, presumably, be considerably less than

TABLE I
DATA FOR ^{230}Th FROM 0.682 TO 0.750 MeV,^a COMPARED WITH THREE-PARAMETER FIT

E (MeV)	5.0°	12.5°	17.5°	22.5°	27.5°	32.7°	37.7°	42.5°
0.682	$\frac{2.11 \pm 0.36}{1.88}$	$\frac{1.29 \pm 0.26}{1.81}$	$\frac{1.64 \pm 0.33}{1.72}$	$\frac{1.92 \pm 0.24}{1.62}$	$\frac{1.87 \pm 0.21}{1.51}$	$\frac{1.35 \pm 0.16}{1.40}$	$\frac{1.01 \pm 0.20}{1.29}$	$\frac{1.14 \pm 0.19}{1.20}$
0.715	$\frac{1.52 \pm 0.22}{1.81}$	$\frac{1.84 \pm 0.22}{1.75}$	$\frac{1.92 \pm 0.19}{1.69}$	$\frac{1.71 \pm 0.16}{1.62}$	$\frac{1.56 \pm 0.14}{1.54}$	$\frac{1.47 \pm 0.12}{1.45}$	$\frac{1.24 \pm 0.16}{1.37}$	$\frac{1.24 \pm 0.14}{1.29}$
0.730	$\frac{3.52 \pm 0.41}{3.07}$	$\frac{2.63 \pm 0.31}{2.87}$	$\frac{2.53 \pm 0.26}{2.66}$	$\frac{2.28 \pm 0.22}{2.40}$	$\frac{2.05 \pm 0.19}{2.13}$	$\frac{1.78 \pm 0.17}{1.84}$	$\frac{1.51 \pm 0.21}{1.58}$	$\frac{1.50 \pm 0.20}{1.36}$
0.740	$\frac{1.94 \pm 0.16}{1.87}$	$\frac{1.80 \pm 0.13}{1.81}$	$\frac{1.84 \pm 0.12}{1.74}$	$\frac{1.64 \pm 0.10}{1.66}$	$\frac{1.48 \pm 0.08}{1.57}$	$\frac{1.28 \pm 0.07}{1.47}$	$\frac{1.33 \pm 0.10}{1.38}$	$\frac{1.45 \pm 0.09}{1.30}$
0.750	$\frac{2.08 \pm 0.11}{2.05}$	$\frac{1.94 \pm 0.10}{1.96}$	$\frac{1.97 \pm 0.08}{1.87}$	$\frac{1.75 \pm 0.07}{1.75}$	$\frac{1.55 \pm 0.06}{1.62}$	$\frac{1.39 \pm 0.05}{1.49}$	$\frac{1.30 \pm 0.07}{1.37}$	$\frac{1.37 \pm 0.07}{1.26}$

^aSource of data: Yuen et al. (Ref. 3)

the uncertainty in the individual points. For this reason, the quoted error in the normalized data was calculated under the assumption that there is no uncertainty in $\frac{1}{a_0}$. The number of data points in Table I which differ from the fit by more than the experimental error is about what one would expect from statistical fluctuation.

From 0.858 to 1.230 MeV, the angular distribution has been measured by Vorotnikov et al.⁴ These data and our three-parameter fit are presented in Table II in the same format as that used in Table I. Because of the small number of angles in this case, we are to some extent fitting the statistical fluctuations in the data.

It should be noted that the data in Ref. 4 were normalized to a measured point at 90°. Thus, the value of $W(90^\circ)$ is 1.000 with an error of zero. We have assumed that the uncertainty, σ , in the 90° measurement is similar to the uncertainty in the other points. The experimental errors quoted in Ref. 4 are then roughly $\sqrt{2} \sigma$. We have put the 90° point on an equal footing by assigning an error of 1σ to all points at a given energy in Table II and, in fitting the data, the 90° point is given the same weight as the others. Since the data are

normalized to the value of the fit at 90°, the normalized experimental point at 90°, in general, will not be equal to unity.

From 1.25 to 3.00 MeV, we have chosen the data of Simmons and Henkel.⁵ Their data and our fit are presented in Table III. The authors here have normalized to their experimental point at 90° in the same manner as Vorotnikov et al.,⁴ and the procedure described in the preceding paragraph has been repeated.

The three measurements of $W(\theta)$ described above provide a fairly complete description of the angular distribution of fragments from ^{230}Th in the energy range from threshold to 3.0 MeV. The results of our fitting procedure are given in Table IV. The coefficients α_2 and α_4 , when substituted in Eq. (4), give the distributions listed in the denominator of each entry in Tables I, II, and III. The third parameter used in the fitting, a_0 , is of no further interest here. Also given in Table IV are the values $R(15^\circ)$ and $R(80^\circ)$, calculated using Eq. (6). In our cross-section calculations for ^{230}Th ,¹ $R(\theta)$ was obtained as a function of neutron energy by linear interpolation between the values in Table IV.

TABLE I (contd.)

E (MeV)	47.5°	52.5°	58.7°	66.2°	70.5°	77.5°	82.5°	87.5°
0.682	$\frac{1.23 \pm 0.19}{1.12}$	$\frac{1.10 \pm 0.17}{1.06}$	$\frac{1.16 \pm 0.14}{1.01}$	$\frac{0.82 \pm 0.13}{0.99}$	$\frac{0.78 \pm 0.15}{0.98}$	$\frac{0.92 \pm 0.17}{0.99}$	$\frac{1.07 \pm 0.18}{1.00}$	$\frac{1.18 \pm 0.18}{1.00}$
0.715	$\frac{1.21 \pm 0.14}{1.22}$	$\frac{1.10 \pm 0.12}{1.16}$	$\frac{0.98 \pm 0.09}{1.10}$	$\frac{1.30 \pm 0.12}{1.05}$	$\frac{1.12 \pm 0.13}{1.03}$	$\frac{0.94 \pm 0.12}{1.01}$	$\frac{0.95 \pm 0.12}{1.00}$	$\frac{0.97 \pm 0.12}{1.00}$
0.730	$\frac{1.28 \pm 0.17}{1.17}$	$\frac{1.06 \pm 0.15}{1.04}$	$\frac{0.90 \pm 0.11}{0.94}$	$\frac{0.94 \pm 0.12}{0.91}$	$\frac{1.06 \pm 0.16}{0.92}$	$\frac{0.90 \pm 0.14}{0.96}$	$\frac{0.92 \pm 0.14}{0.98}$	$\frac{0.96 \pm 0.14}{1.00}$
0.740	$\frac{1.27 \pm 0.09}{1.22}$	$\frac{1.08 \pm 0.08}{1.16}$	$\frac{1.13 \pm 0.06}{1.09}$	$\frac{1.19 \pm 0.07}{1.04}$	$\frac{1.06 \pm 0.08}{1.02}$	$\frac{0.97 \pm 0.07}{1.01}$	$\frac{0.96 \pm 0.07}{1.00}$	$\frac{0.94 \pm 0.07}{1.00}$
0.750	$\frac{1.16 \pm 0.06}{1.17}$	$\frac{1.02 \pm 0.05}{1.10}$	$\frac{1.09 \pm 0.04}{1.04}$	$\frac{1.14 \pm 0.05}{1.00}$	$\frac{1.07 \pm 0.05}{0.99}$	$\frac{0.95 \pm 0.05}{0.99}$	$\frac{0.94 \pm 0.05}{1.00}$	$\frac{0.93 \pm 0.05}{1.00}$

TABLE II

DATA FOR ^{230}Th FROM 0.858 TO 1.230 MeV,^a COMPARED WITH THREE-PARAMETER FIT

E (MeV)	12°	30°	60°	90°
0.858	$\frac{1.36 \pm 0.06}{1.33}$	$\frac{1.07 \pm 0.06}{1.13}$	$\frac{1.00 \pm 0.06}{0.95}$	$\frac{0.97 \pm 0.06}{1.00}$
0.911	$\frac{1.00 \pm 0.04}{1.03}$	$\frac{1.09 \pm 0.04}{1.03}$	$\frac{0.96 \pm 0.04}{1.02}$	$\frac{1.03 \pm 0.04}{1.00}$
0.925	$\frac{0.90 \pm 0.04}{0.89}$	$\frac{0.92 \pm 0.04}{0.93}$	$\frac{1.00 \pm 0.04}{0.99}$	$\frac{1.00 \pm 0.04}{1.00}$
0.964	$\frac{0.77 \pm 0.04}{0.80}$	$\frac{1.00 \pm 0.04}{0.93}$	$\frac{1.00 \pm 0.04}{1.05}$	$\frac{1.03 \pm 0.04}{1.00}$
1.015	$\frac{0.94 \pm 0.04}{0.95}$	$\frac{1.02 \pm 0.04}{1.02}$	$\frac{1.04 \pm 0.04}{1.05}$	$\frac{1.00 \pm 0.04}{1.00}$
1.066	$\frac{1.51 \pm 0.04}{1.52}$	$\frac{1.39 \pm 0.04}{1.37}$	$\frac{1.09 \pm 0.04}{1.10}$	$\frac{1.01 \pm 0.04}{1.00}$
1.122	$\frac{1.54 \pm 0.04}{1.55}$	$\frac{1.45 \pm 0.04}{1.42}$	$\frac{1.11 \pm 0.04}{1.13}$	$\frac{1.01 \pm 0.04}{1.00}$
1.176	$\frac{1.45 \pm 0.04}{1.43}$	$\frac{1.28 \pm 0.04}{1.32}$	$\frac{1.13 \pm 0.04}{1.09}$	$\frac{0.98 \pm 0.04}{1.00}$
1.200	$\frac{1.38 \pm 0.02}{1.37}$	$\frac{1.30 \pm 0.02}{1.30}$	$\frac{1.12 \pm 0.02}{1.11}$	$\frac{1.00 \pm 0.02}{1.00}$
1.230	$\frac{1.41 \pm 0.04}{1.37}$	$\frac{1.17 \pm 0.04}{1.23}$	$\frac{1.09 \pm 0.04}{1.03}$	$\frac{0.97 \pm 0.04}{1.00}$

^aSource of data: Vorotnikov et al. (Ref. 4)

TABLE III

DATA FOR ^{230}Th FROM 1.25 TO 3.00 MeV,^a COMPARED WITH THREE-PARAMETER FIT

E (MeV)	10°	22.5°	45°	67.5°	90°
1.25	$\frac{1.38 \pm 0.06}{1.40}$	$\frac{1.32 \pm 0.06}{1.31}$	$\frac{1.15 \pm 0.06}{1.10}$	$\frac{0.90 \pm 0.05}{1.01}$	$\frac{1.07 \pm 0.05}{1.00}$
1.50	$\frac{0.93 \pm 0.05}{0.91}$	$\frac{0.93 \pm 0.05}{0.96}$	$\frac{1.05 \pm 0.05}{1.04}$	$\frac{1.05 \pm 0.04}{1.03}$	$\frac{0.99 \pm 0.04}{1.00}$
1.75	$\frac{1.28 \pm 0.04}{1.26}$	$\frac{1.18 \pm 0.04}{1.21}$	$\frac{1.11 \pm 0.04}{1.10}$	$\frac{1.04 \pm 0.04}{1.02}$	$\frac{0.99 \pm 0.04}{1.00}$
2.00	$\frac{1.32 \pm 0.04}{1.37}$	$\frac{1.34 \pm 0.04}{1.27}$	$\frac{1.05 \pm 0.04}{1.05}$	$\frac{0.93 \pm 0.04}{0.98}$	$\frac{1.04 \pm 0.04}{1.00}$
2.10	$\frac{1.62 \pm 0.05}{1.60}$	$\frac{1.47 \pm 0.06}{1.49}$	$\frac{1.20 \pm 0.05}{1.22}$	$\frac{1.09 \pm 0.05}{1.04}$	$\frac{0.97 \pm 0.05}{1.00}$
2.50	$\frac{1.22 \pm 0.05}{1.24}$	$\frac{1.21 \pm 0.05}{1.21}$	$\frac{1.20 \pm 0.05}{1.13}$	$\frac{0.91 \pm 0.04}{1.04}$	$\frac{1.08 \pm 0.04}{1.00}$
3.00	$\frac{1.21 \pm 0.02}{1.23}$	$\frac{1.22 \pm 0.02}{1.19}$	$\frac{1.10 \pm 0.02}{1.10}$	$\frac{1.00 \pm 0.02}{1.02}$	$\frac{1.01 \pm 0.02}{1.00}$

^aSource of data: Simmons and Henkel (Ref. 5)

TABLE IV
FITTING PARAMETERS
AND ANGULAR CORRECTION FACTORS FOR ^{230}Th

E (MeV)	α_2	α_4	R(15°)	R(80°)	Ref.
0.682	-0.272	1.172	1.544	0.868	3
0.715	0.187	0.634	1.452	0.846	3
0.730	-1.069	3.177	2.164	0.759	3
0.740	0.142	0.743	1.488	0.840	3
0.750	-0.219	1.288	1.618	0.840	3
0.858	-0.414	0.789	1.275	0.969	4
0.911	0.072	-0.046	1.012	0.987	4
0.925	-0.036	-0.083	0.921	1.028	4
0.964	0.340	-0.569	0.822	1.010	4
1.015	0.294	-0.364	0.934	0.984	4
1.066	0.347	0.202	1.297	0.874	4
1.122	0.515	0.062	1.296	0.858	4
1.176	0.338	0.116	1.247	0.890	4
1.200	0.460	-0.075	1.198	0.891	4
1.230	0.023	0.382	1.249	0.923	4
1.250	-0.014	0.440	1.264	0.923	5
1.500	0.280	-0.386	0.911	0.992	5
1.750	0.124	0.146	1.161	0.938	5
2.000	-0.195	0.594	1.267	0.944	5
2.100	0.237	0.395	1.351	0.870	5
2.500	0.279	-0.038	1.131	0.929	5
3.000	0.149	0.087	1.138	0.941	5

V. DISTRIBUTIONS FOR ^{232}Th

A detailed study of the fission fragment angular distributions for ^{232}Th has recently been published by Ermagambetov and Smirenkin.² Their results agree with recent measurements at 1.4 and 1.6 MeV by Behkami et al.,⁶ but disagree with measurements by Lo Nigro and Milone⁷ as well as those by Henkel and Brolley.⁸ We have chosen to use the data of Ermagambetov and Smirenkin in the energy range from threshold to 2.3 MeV.

Ermagambetov and Smirenkin have conveniently published Legendre polynomial fitting coefficients for their data. For the sake of consistency, we have converted their coefficients into the equivalent set of cosine coefficients, α_{2n} . $R(\theta)$ is then calculated using Eq. (6). The converted fitting coefficients are given in Table V, along with $R(15^\circ)$ and $R(80^\circ)$. The values at 3.0 MeV are based on a measurement of $W(0^\circ)/W(90^\circ)$ by Henkel and Brolley.⁸ In the absence of other information, we have set α_4 and higher terms equal to zero at this energy.

TABLE V
FITTING PARAMETERS
AND ANGULAR CORRECTION FACTORS FOR $^{232}\text{Th}^a$

E (MeV)	α_2	α_4	α_6	R(15°)	R(80°)
0.95	-0.502	1.245	-0.159	1.403	0.931
1.00	-0.253	0.871	-0.029	1.380	0.915
1.10	0.262	-0.632	1.400	1.577	0.868
1.15	1.101	-2.135	1.848	1.387	0.857
1.20	0.828	-0.553	0.332	1.287	0.845
1.25	0.307	-0.050	0.072	1.180	0.915
1.30	-0.378	1.827	-1.198	1.183	0.927
1.35	-0.108	1.038	-1.069	0.917	0.979
1.40	-0.599	2.501	-2.164	0.868	0.993
1.45	0.218	0.313	-0.823	0.793	0.989
1.50	0.244	0.414	-1.141	0.661	1.007
1.55	0.651	-0.514	-0.737	0.556	1.010
1.60	0.542	0.177	-1.314	0.576	0.988
1.65	0.485	-0.649	-0.303	0.649	1.026
1.70	0.946	-1.138	-0.087	0.764	0.956
1.80	-0.526	1.571	-1.040	1.042	0.995
2.00	-0.108	0.823	-0.318	1.253	0.921
2.30	0.574	-0.774	0.808	1.318	0.883
3.00 ^b	0.390	-	-	1.207	0.895

^aSource of data (except at 3.00 MeV): Ermagambetov and Smirenkin (Ref. 2)

^bSource of data: Henkel and Brolley (Ref. 8)

VI. DISTRIBUTIONS FOR ^{231}Pa

The distribution of fragments from ^{231}Pa has been recently measured over the energy range from 0.140 to 1.290 MeV by Vorotnikov et al.⁹ They also have measured $W(0^\circ)/W(90^\circ)$ at 4.0 and 5.0 MeV. Their

data are normalized to the experimental point at 90° so the error treatment discussed above was applied. The data, experimental uncertainties, and our three-parameter fit are given in Table VI, using the same format as that used in Table I. As in the case of

TABLE VI
DATA FOR ^{231}Pa ,^a COMPARED WITH THREE-PARAMETER FIT

<u>E</u> <u>(MeV)</u>	<u>12°</u>	<u>30°</u>	<u>60°</u>	<u>90°</u>
0.140	$\frac{0.74 \pm 0.07}{0.67}$	$\frac{0.66 \pm 0.07}{0.78}$	$\frac{1.07 \pm 0.08}{0.96}$	$\frac{0.95 \pm 0.07}{1.00}$
0.165	$\frac{0.48 \pm 0.04}{0.49}$	$\frac{0.72 \pm 0.04}{0.71}$	$\frac{0.98 \pm 0.04}{1.00}$	$\frac{1.00 \pm 0.04}{1.00}$
0.213	$\frac{0.81 \pm 0.11}{0.85}$	$\frac{1.04 \pm 0.11}{0.96}$	$\frac{0.98 \pm 0.11}{1.05}$	$\frac{1.04 \pm 0.11}{1.00}$
0.280	$\frac{0.86 \pm 0.05}{0.87}$	$\frac{0.96 \pm 0.05}{0.94}$	$\frac{0.99 \pm 0.05}{1.01}$	$\frac{1.01 \pm 0.05}{1.00}$
0.350	$\frac{0.80 \pm 0.04}{0.78}$	$\frac{0.82 \pm 0.04}{0.86}$	$\frac{1.01 \pm 0.05}{0.98}$	$\frac{0.98 \pm 0.05}{1.00}$
0.410	$\frac{0.93 \pm 0.04}{0.93}$	$\frac{0.98 \pm 0.04}{0.98}$	$\frac{1.02 \pm 0.05}{1.02}$	$\frac{1.00 \pm 0.05}{1.00}$
0.470	$\frac{0.99 \pm 0.04}{1.00}$	$\frac{0.99 \pm 0.04}{0.99}$	$\frac{0.98 \pm 0.04}{0.99}$	$\frac{1.00 \pm 0.04}{0.99}$
0.575	$\frac{1.18 \pm 0.04}{1.18}$	$\frac{1.13 \pm 0.04}{1.13}$	$\frac{1.03 \pm 0.04}{1.03}$	$\frac{1.00 \pm 0.04}{1.00}$
0.625	$\frac{1.13 \pm 0.04}{1.14}$	$\frac{1.20 \pm 0.04}{1.18}$	$\frac{1.09 \pm 0.04}{1.11}$	$\frac{1.01 \pm 0.04}{1.00}$
0.670	$\frac{0.97 \pm 0.03}{0.98}$	$\frac{1.01 \pm 0.03}{1.01}$	$\frac{1.01 \pm 0.03}{1.02}$	$\frac{1.00 \pm 0.03}{1.00}$
0.715	$\frac{1.14 \pm 0.03}{1.17}$	$\frac{1.21 \pm 0.03}{1.16}$	$\frac{1.02 \pm 0.03}{1.07}$	$\frac{1.02 \pm 0.03}{1.00}$
0.775	$\frac{1.12 \pm 0.03}{1.13}$	$\frac{1.18 \pm 0.03}{1.16}$	$\frac{1.09 \pm 0.03}{1.10}$	$\frac{1.01 \pm 0.03}{1.00}$
0.865	$\frac{1.09 \pm 0.03}{1.09}$	$\frac{1.08 \pm 0.03}{1.08}$	$\frac{1.04 \pm 0.03}{1.04}$	$\frac{1.00 \pm 0.03}{1.00}$
0.970	$\frac{1.12 \pm 0.03}{1.12}$	$\frac{1.13 \pm 0.03}{1.11}$	$\frac{1.04 \pm 0.03}{1.05}$	$\frac{1.01 \pm 0.03}{1.00}$
1.080	$\frac{1.13 \pm 0.04}{1.14}$	$\frac{1.11 \pm 0.04}{1.11}$	$\frac{1.03 \pm 0.04}{1.04}$	$\frac{1.00 \pm 0.04}{1.00}$
1.185	$\frac{1.12 \pm 0.03}{1.12}$	$\frac{1.07 \pm 0.04}{1.09}$	$\frac{1.04 \pm 0.04}{1.02}$	$\frac{1.00 \pm 0.04}{1.00}$
1.290	$\frac{1.10 \pm 0.03}{1.11}$	$\frac{1.13 \pm 0.03}{1.11}$	$\frac{1.03 \pm 0.03}{1.05}$	$\frac{1.01 \pm 0.03}{1.00}$

^aSource of data: Vorotnikov et al. (Ref. 9)

²³⁰Th (Table II), there is an excess of parameters, so we are to some extent fitting statistical fluctuations in the data. The fitting parameters, α_2 and α_4 , are given in Table VII, along with the calculated values of R(15°) and R(80°). The values for 4.000 MeV are derived from the measured 0°/90° ratio under the assumption that α_4 and higher terms are zero.

VII. DISTRIBUTIONS FOR ²³⁹Pu

Angular distributions for ²³⁹Pu have been measured from 0.15 to 1.50 MeV by Huizenga et al.¹⁰ Their data, quoted standard errors, and our two-parameter fit are given in Table VIII, using the format of Table I. The simple form, $1 + \alpha_2 \cos^2\theta$, gives an adequate fit throughout this energy region. (The second parameter used in fitting the data is the normalization factor, a_0 .)

Since only one measurement below 0.4 MeV is reported by Huizenga et al.,¹⁰ we have chosen a different set of data in the low-energy region. Smirenkin et al.¹¹ have measured the ratio W(0°)/W(90°) at a large number of energies below 0.4 MeV. They find that the 0°/90° ratio rises almost linearly with neutron energy from 1.00 at 0.0 MeV, to 1.12 at 0.225 MeV, and then remains nearly constant from 0.225 to 0.4 MeV.

On the basis of Huizenga's data (Table VIII), it seems safe to assume that the form $1 + \alpha_2 \cos^2\theta$ is adequate. This assumption allows one to calculate α_2 directly from the 0°/90° ratios measured by Smirenkin et al.¹¹ in this energy region.

Above 1.0 MeV, we have used the data of Simmons, as reported by Griffin.¹² His data, experimental errors, and our two-parameter fit are given in Table IX. Since his data were normalized to an experimental point at 90°, the

errors were treated the same as those shown in Table II.

The fitting parameter, α_2 , and the calculated angular correction factors R(15°) and R(80°) are

TABLE VII
FITTING PARAMETERS

AND ANGULAR CORRECTION FACTORS FOR ²³¹Pa^a

E (MeV)	α_2	α_4	R(15°)	R(80°)
0.140	-0.078	-0.278	0.746	1.086
0.165	0.162	-0.728	0.570	1.105
0.213	0.345	-0.522	0.858	0.999
0.280	0.099	-0.244	0.894	1.019
0.350	-0.057	-0.179	0.837	1.056
0.410	0.138	-0.220	0.935	1.002
0.470	-0.066	0.064	1.004	1.007
0.575	0.107	0.086	1.116	0.953
0.625	0.553	-0.420	1.046	0.924
0.670	0.119	-0.148	0.972	0.994
0.715	0.299	-0.124	1.090	0.938
0.775	0.512	-0.395	1.038	0.930
0.865	0.168	-0.080	1.045	0.966
0.970	0.220	-0.094	1.066	0.954
1.080	0.149	-0.008	1.080	0.958
1.185	0.087	0.037	1.075	0.967
1.290	0.233	-0.119	1.057	0.955
4.000	0.130	-	1.075	0.962

^aSource of data: Vorotnikov et al. (Ref. 9)

TABLE VIII

DATA FOR ^{239}Pu FROM 0.150 TO 1.500 MeV, ^a COMPARED WITH TWO-PARAMETER FIT

E (MeV)	3.7°	24.0°	37.2°	54.7°	72.3°	90.0°
0.150	$\frac{1.077 \pm 0.014}{1.075}$	$\frac{1.052 \pm 0.014}{1.063}$	$\frac{1.067 \pm 0.015}{1.048}$	$\frac{1.011 \pm 0.014}{1.025}$	$\frac{1.000 \pm 0.014}{1.007}$	$\frac{1.010 \pm 0.012}{1.000}$
0.400	$\frac{1.137 \pm 0.021}{1.129}$	$\frac{1.085 \pm 0.016}{1.108}$	$\frac{1.096 \pm 0.017}{1.082}$	$\frac{1.051 \pm 0.016}{1.043}$	$\frac{1.010 \pm 0.016}{1.012}$	$\frac{0.996 \pm 0.013}{1.000}$
0.475	$\frac{1.103 \pm 0.012}{1.096}$	$\frac{1.085 \pm 0.013}{1.080}$	$\frac{1.054 \pm 0.012}{1.061}$	$\frac{1.005 \pm 0.012}{1.032}$	$\frac{1.036 \pm 0.013}{1.009}$	$\frac{0.996 \pm 0.010}{1.000}$
0.550	$\frac{1.131 \pm 0.013}{1.135}$	$\frac{1.119 \pm 0.014}{1.113}$	$\frac{1.093 \pm 0.014}{1.086}$	$\frac{1.022 \pm 0.013}{1.045}$	$\frac{1.022 \pm 0.013}{1.012}$	$\frac{1.003 \pm 0.011}{1.000}$
0.600	$\frac{1.139 \pm 0.011}{1.130}$	$\frac{1.103 \pm 0.012}{1.109}$	$\frac{1.075 \pm 0.011}{1.083}$	$\frac{1.044 \pm 0.011}{1.044}$	$\frac{1.025 \pm 0.012}{1.012}$	$\frac{0.992 \pm 0.011}{1.000}$
0.700	$\frac{1.126 \pm 0.014}{1.113}$	$\frac{1.093 \pm 0.015}{1.095}$	$\frac{1.060 \pm 0.015}{1.072}$	$\frac{1.026 \pm 0.014}{1.038}$	$\frac{1.012 \pm 0.015}{1.010}$	$\frac{1.012 \pm 0.012}{1.000}$
0.800	$\frac{1.126 \pm 0.012}{1.119}$	$\frac{1.098 \pm 0.012}{1.100}$	$\frac{1.073 \pm 0.012}{1.076}$	$\frac{1.029 \pm 0.011}{1.040}$	$\frac{1.027 \pm 0.012}{1.011}$	$\frac{0.994 \pm 0.010}{1.000}$
0.900	$\frac{1.109 \pm 0.012}{1.115}$	$\frac{1.099 \pm 0.012}{1.096}$	$\frac{1.070 \pm 0.012}{1.073}$	$\frac{1.056 \pm 0.012}{1.038}$	$\frac{1.001 \pm 0.012}{1.011}$	$\frac{0.999 \pm 0.010}{1.000}$
1.000	$\frac{1.131 \pm 0.015}{1.130}$	$\frac{1.106 \pm 0.015}{1.109}$	$\frac{1.089 \pm 0.015}{1.083}$	$\frac{1.035 \pm 0.014}{1.044}$	$\frac{1.009 \pm 0.015}{1.012}$	$\frac{1.007 \pm 0.012}{1.000}$
1.100	$\frac{1.120 \pm 0.012}{1.121}$	$\frac{1.097 \pm 0.012}{1.101}$	$\frac{1.093 \pm 0.012}{1.077}$	$\frac{1.019 \pm 0.011}{1.041}$	$\frac{1.029 \pm 0.012}{1.011}$	$\frac{0.993 \pm 0.010}{1.000}$
1.200	$\frac{1.135 \pm 0.013}{1.133}$	$\frac{1.117 \pm 0.014}{1.112}$	$\frac{1.079 \pm 0.014}{1.085}$	$\frac{1.039 \pm 0.013}{1.045}$	$\frac{1.005 \pm 0.014}{1.012}$	$\frac{1.012 \pm 0.011}{1.000}$
1.350	$\frac{1.124 \pm 0.013}{1.122}$	$\frac{1.109 \pm 0.013}{1.102}$	$\frac{1.073 \pm 0.013}{1.078}$	$\frac{1.025 \pm 0.012}{1.041}$	$\frac{1.024 \pm 0.012}{1.011}$	$\frac{1.000 \pm 0.010}{1.000}$
1.500	$\frac{1.160 \pm 0.013}{1.174}$	$\frac{1.154 \pm 0.013}{1.146}$	$\frac{1.128 \pm 0.013}{1.111}$	$\frac{1.052 \pm 0.012}{1.058}$	$\frac{1.006 \pm 0.012}{1.016}$	$\frac{1.006 \pm 0.012}{1.000}$

^aSource of data: Huizenga et al. (Ref. 10)

TABLE IX

DATA FOR ^{239}Pu FROM 1.00 TO 3.00 MeV, ^a COMPARED WITH TWO-PARAMETER FIT

E (MeV)	10.0°	22.5°	45.0°	67.5°	90.0°
1.00	$\frac{1.067 \pm 0.007}{1.073}$	$\frac{1.073 \pm 0.008}{1.064}$	$\frac{1.036 \pm 0.007}{1.038}$	$\frac{1.015 \pm 0.008}{1.011}$	$\frac{0.997 \pm 0.007}{1.000}$
1.50	$\frac{1.096 \pm 0.008}{1.097}$	$\frac{1.087 \pm 0.008}{1.085}$	$\frac{1.047 \pm 0.008}{1.050}$	$\frac{1.016 \pm 0.008}{1.015}$	$\frac{1.000 \pm 0.008}{1.000}$
1.75	$\frac{1.103 \pm 0.008}{1.101}$	$\frac{1.086 \pm 0.008}{1.089}$	$\frac{1.053 \pm 0.008}{1.052}$	$\frac{1.021 \pm 0.007}{1.015}$	$\frac{0.995 \pm 0.007}{1.000}$
2.00	$\frac{1.108 \pm 0.008}{1.100}$	$\frac{1.073 \pm 0.008}{1.088}$	$\frac{1.060 \pm 0.011}{1.051}$	$\frac{1.019 \pm 0.013}{1.015}$	$\frac{0.994 \pm 0.008}{1.000}$
2.25	$\frac{1.107 \pm 0.006}{1.108}$	$\frac{1.097 \pm 0.005}{1.095}$	$\frac{1.052 \pm 0.005}{1.056}$	$\frac{1.022 \pm 0.006}{1.016}$	$\frac{0.996 \pm 0.005}{1.000}$
2.50	$\frac{1.114 \pm 0.005}{1.115}$	$\frac{1.105 \pm 0.005}{1.101}$	$\frac{1.054 \pm 0.005}{1.059}$	$\frac{1.022 \pm 0.005}{1.017}$	$\frac{0.998 \pm 0.005}{1.000}$
2.75	$\frac{1.116 \pm 0.004}{1.114}$	$\frac{1.102 \pm 0.004}{1.100}$	$\frac{1.051 \pm 0.004}{1.059}$	$\frac{1.019 \pm 0.004}{1.017}$	$\frac{1.002 \pm 0.004}{1.000}$
3.00	$\frac{1.108 \pm 0.004}{1.104}$	$\frac{1.087 \pm 0.004}{1.092}$	$\frac{1.052 \pm 0.004}{1.054}$	$\frac{1.019 \pm 0.004}{1.016}$	$\frac{0.998 \pm 0.004}{1.000}$

^aSource of data: Simmons, Reported in Griffin's Report (Ref. 12)

presented in Table X. Above 0.225 MeV, the values of $R(\theta)$ are quite insensitive to energy; consequently, we have averaged the results in groups of from three to five. For example, the value of α_2 listed at 0.457 MeV is just the average of the values obtained from fitting Huizenga's data at 0.400, 0.475, and 0.550 MeV. The value listed at 1.300 MeV is the average of three Huizenga points with two Simmons points. The values at zero energy in Table X are included explicitly in order to emphasize that linear interpolation is intended between 0.0 and 0.225 MeV.

TABLE X
FITTING PARAMETERS

AND ANGULAR CORRECTION FACTORS FOR ^{239}Pu

<u>E</u> <u>(MeV)</u>	<u>α_2</u>	<u>R(15°)</u>	<u>R(80°)</u>	<u>Ref.</u>
0.000	0.000	1.000	1.000	11
0.225	0.120	1.069	0.965	11
0.475	0.120	1.069	0.965	10
0.700	0.121	1.070	0.965	10
1.000	0.122	1.071	0.964	10
1.300	0.116	1.067	0.966	10,12
2.000	0.106	1.061	0.969	12
3.000	0.112	1.065	0.967	12

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