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The Fission Cross Section Ratios and Error Analysis for Ten Thorium, Uranium, Neptunium, and Plutonium Isotopes at 14.74 MeV Neutron Energy

by

J.W. Meadows

March 1987

ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.

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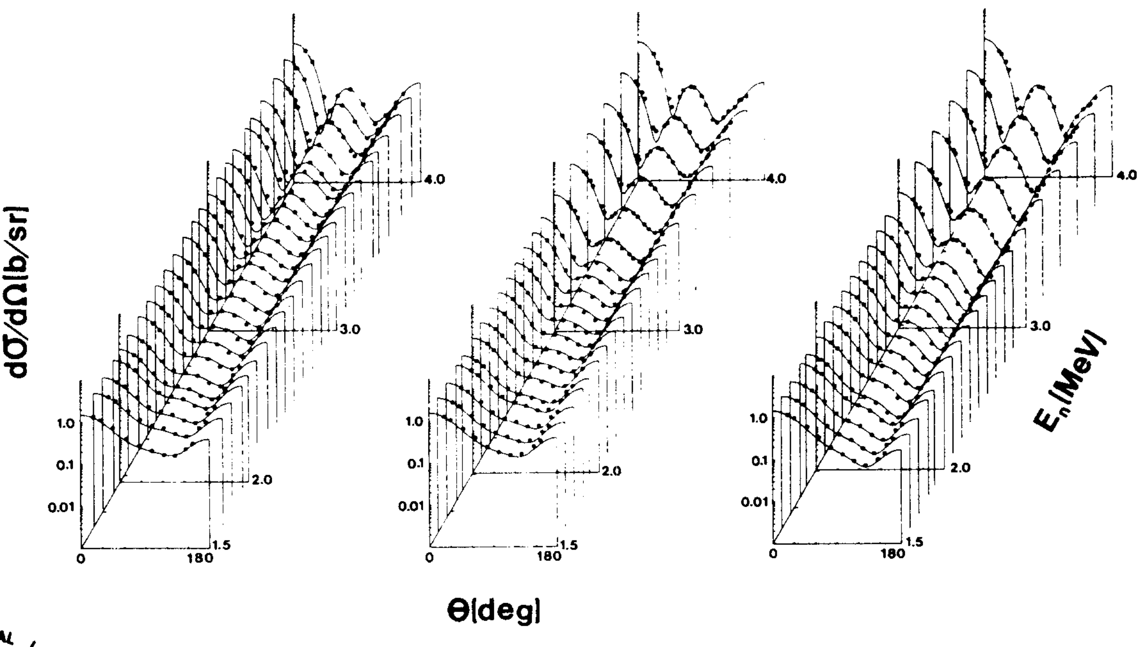

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ANL/NDM-98

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Keywords: NUCLEAR REACTIONS, FISSION ^{230}Th, ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{242}Pu (n,f); E_n = 14.7 MeV; Cross Section Ratios; Cross Sections.

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*Work supported by the U.S. Department of Energy, Basic Energy Science Programs under contract W-31-109-ENG-38.

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ABSTRACT

The error information from the recent measurements of the fission cross section ratios of nine isotopes, ^{230}Th, ^{232}Th, ^{233}U, ^{234}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, and ^{242}Pu, relative to ^{235}U at 14.74 MeV neutron energy was used to calculate their correlations. The remaining 36 non-trivial and non-reciprocal cross section ratios and their errors were determined and compared to evaluated (ENDF/B-V) values. There are serious differences but it was concluded that the reduction of three of the evaluated cross sections would remove most of them. The cross sections to be reduced are ^{230}Th - 13 %, ^{237}Np - 9.6 % and ^{239}Pu - 7.6 %.

*This work supported by the U. S. Department of Energy, Basic Energy Science Programs under contract W-31-109-ENG-38.

INTRODUCTION

The measurement of the fission cross section ratios of ^{230}Th, ^{232}Th, ^{233}U, ^{234}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, and ^{242}Pu, relative to ^{235}U at an average neutron energy of 14.74 MeV was recently reported[1]. The other fission cross section ratios that can be derived from these measurements are also useful and since the derived values will be ratios of the measured quantities the common systematic errors will cancel. However, reliable errors can be estimated for the derived values only if there is sufficient information concerning the measurement errors and their correlations. This report extends the discussion of the errors in ref. (1) using methods described by Smith[2,4] and Evain et. al.[3] The error table and the correlation matrix for the original data are given explicitly. The weighted averages of the nine distinct measured ratios and their correlation matrix are calculated and the remaining 36 possible fission cross section ratios and their errors are derived and compared with the evaluated data in ENDF/B-V[5].

PROCEDURES

In this work there are 42 measurements of 9 fission cross section ratios. The object of the study is to obtain the best value for each of the cross section ratios, to combine them to obtain all possible cross section ratios and to properly calculate the errors in the results from the error information provided with the experimental data. The problem of averaging like quantitites is discussed in general terms in ref. 2 and explicitly in ref. 3, while the generation of the covariance matrix for a set of averaged quantities is covered in ref. 4. Only those results relevant to this report are given here.

Let R_i denote the experimental value for the i^{th} cross section ratio measurement. The subset consisting of all attempts to measure cross section ratio α may be expressed collectively as a vector $\vec{R}_\alpha$ so that

$$\vec{R}_\alpha \simeq \bar{A}_\alpha \cdot r_\alpha \tag{1}$$

where $\bar{A}_\alpha$ is a column matrix with n_α elements all equal to 1 and r_α represents the "true" cross section ratio. The least squares solution to eq. (1) is

$$r_\alpha = C_\alpha \cdot \bar{A}_\alpha^T \cdot \bar{V}_{\alpha\alpha}^{-1} \cdot \vec{R}_\alpha \tag{2}$$

$$C_\alpha = (\bar{A}_\alpha^T \cdot \bar{V}_{\alpha\alpha}^{-1} \cdot \bar{A}_\alpha)^{-1} \tag{3}$$

where T represents matrix transposition, -1 is inversion and the scaler C_α is the variance of r_α. Thus the standard deviation is $C_\alpha^{1/2}$. $\bar{V}_{\alpha\alpha}$ is the covariance matrix for $\vec{R}_\alpha$ and has elements of the form

$$V_{ij} = \sum_l S_{ijl}\, e_{il}\, e_{jl} \tag{4}$$

where e_{il} is the error component l for the i^{th} measurement and S_{ijl} is the correlation coefficient for measurements i and j with respect to error component l. The submatrix, $\bar{V}_{\alpha\alpha}$, includes only those elements V_{ij} from the parent matrix, $\bar{V}$, for all data which correspond to measurements of the ratio α. The sum is over all error components. While the covariance matrix is more convenient for calculation, the correlation matrix, with elements M_{ij}, may provide more graphic information. The relation between them is

$$M_{ij} = V_{ij}/(E_i\, E_j) \tag{6}$$

$$E_i^2 = \sum_l e_{il}^2 \tag{7}$$

Chi-squared is a useful quantity and may be expressed as

$$\aleph_\alpha^2 = (\vec{R}_\alpha - \bar{A}_\alpha \cdot r_\alpha)^T \ \bar{V}_{\alpha\alpha}^{-1} \ (\vec{R}_\alpha - \bar{A}_\alpha \cdot r_\alpha) \ . \tag{8}$$

The normalized value, $\aleph_\alpha^2/(n_\alpha - 1)$, should be $\simeq 1$ if the scatter of the data is consistent with the errors indicated by $\bar{V}_{\alpha\alpha}$. If $\aleph^2 >> 1$ then the next step may give dubious results. A large $\aleph_\alpha^2$ can be caused by several things but one of them is an underestimation of the uncorrelated error. If a re-examination of the errors does not suggest the cause it is a common practice to introduce additional random error until $\aleph^2 \simeq 1.0$.

In order to properly calculate the errors for quantities obtained by combining r_α, r_β etc. the corresponding covariance or correlation matrix is needed. This may be designated as $\bar{W}$ with elements $W_{\alpha\beta}$ given by

$$W_{\alpha\beta} = \sum_i \ \sum_j \ B_{\beta i} B_{\alpha j} \ V_{ij} \tag{9}$$

where $i \in \{ \beta \}$ and $j \in \{ \alpha \}$. The collection of $B_{\alpha i}$ may be represented by a vector

$$\vec{B}_\alpha = (C_\alpha \ \bar{A}_\alpha^T \ \bar{V}_{\alpha\alpha}^{-1})^T \tag{10}$$

so that the $B_{\alpha j}$ may be obtained from the results of eqs. (3) and (4). Other ratios, $r_{\alpha/\beta}$, are given by

$$r_{\alpha/\beta} = r_\alpha / r_\beta \tag{11}$$

and the fractional error in $r_{\alpha/\beta}$ is

$$F^{1/2}_{\alpha/\beta} = (F_\alpha + F_\beta - 2M_{\alpha\beta}(F_\alpha F_\beta)^{1/2})^{1/2} \qquad (12)$$

where $F_\alpha = C_\alpha/r^2_\alpha$, C_α is given by eq. (3) and $M_{\alpha\beta}$ is contained in the correlation matrix.

THE EXPERIMENTAL DATA AND ERROR INFORMATION

The experimental results, given in Table IX of ref. (1), are repeated in Table I of this report. The errors and their correlations are basically the same as in ref. (1) although they have been rearranged and further consideration has produced a few minor changes. This is described below in detail and the correlations are given explicitly. The complete error table is listed in Table II.

It must be remembered that error estimates are usually the most unreliable values associated with measurements. A few such as counting statistics, have a firm basis. Quantities from the literature keep their accompanying errors unless there are clearly stated reasons for doing otherwise. Uncorrelated errors associated with experimentally determined correction factors can be estimated from the scatter of repeated measurements. However, correlated errors associated with the measurements method are often very subjective estimates. Fortunately, in ratio measurements of similar quantities many of the correlated errors are expected to cancel. Consequently, many of the highly correlated errors are expected to be small compared to some of the uncorrelated ones. In addition, partial correlations were avoided, as far as practical, by the choice of components and by splitting some of the components into correlated and uncorrelated parts.

1. Counting statistics and other random errors. This includes all the statistical errors associated with fission counting, background corrections, extrapolation corrections plus an additional 0.5 % per measurement which is based on the reproducibility of a number of measurements with the same samples. These errors are not uncorrelated in all cases since the same measure-

ment of the fission ratio was used with sample mass ratios obtained from both alpha counting and a measurement of the thermal fission ratio. Thus the correlation is 1.0 within each of the following groups: (8,9), (11,12), (13,14), (27,28), (38,39) and (41,42). All other correlations are zero.

2. Fully correlated error. The following three errors are completely correlated for all measurements.

a. Neutron energy. The error in the fission cross section ratio, R, is

$$\Delta R = (dR/dE) \cdot \Delta E$$

The uncertainty in the average neutron energy is assumed to be ± 0.05 MeV for all measurements.

b. Thickness correction. This part of the error in the thickness correction was assumed to be 0.3 % of the fission cross section for most measurements. For those with exceptionally high alpha decay rates, such as the ^{230}Th and ^{239}Pu deposits, an additional fully correlated error was added because of the generally poor agreement between the calculated thickness correction and the observed extrapolation correction as discussed in ref. 1. This additional error was equal to one half the additional thickness correction needed to move the data points in Fig. 8 of ref. 1 over to the line representing the general trend of the data.

c. Extrapolation correction. This was assumed to be 0.3 % for all measurements.

3. Errors associated with individual unknown deposits. The correlation is 1.0 for all measurements using the same sample. Otherwise it is zero.

a. Thickness correction. This part of the error in the thickness correction was assumed to be 30 % of the calculated correction. It tended to cancel where the sample mass ratio was determined by the thermal fission ratio. In those cases it was assumed to be 15 % of the correction.

b. Extrapolation correction. This part of the error in the extrapolation correction was assumed to be 30 % of the measured correction. Like 3.a. it tended to cancel where the sample mass ratio was determined by the thermal fission ratio. In those cases it was assumed to be 15 % of the correction.

c. Alpha count. The random errors associated with the alpha count were typically 0.3 %. For those measurements where the sample mass ratio was based on the thermal fission ratio it was zero.

4. Errors associated with individual reference deposits. These are similar to those for the unknown deposit described above.

5. The isotopic analysis of the unknown sample material. If the amount of an isotope present was at the 1 % level the error was assumed to be 0.4 % unless there was evidence to the contrary. For major isotopes (> 10 %) the error was negligible. An exception to this is the ^{234}U content of samples 235 5-2 and 5-3 where the error was only 0.2 %. In these measurements such an error only affects the cross section ratio where one of these isotopes is the principal alpha emitter and thus affects the determination of the sample mass by alpha counting. The correlation is 1.0 within the following groups: (1, 2, 3), (4, 5, 6), (7, 8, 9), (15, 18, 19, 20), (21, 23, 25, 26), (27, 30), (29, 32), (33, 34), (35, 36, 38), and (40, 41). Otherwise it is zero.

6. The isotopic analysis of the reference sample material. The errors are the same as section 5. The correlation is 1.0 within the following groups: (1, 2, 6, 12, 15, 21, 22, 27, 34, 36, 38, 40), (2, 3, 5, 7, 16, 19, 25, 30, 31, 33, 35, 41) and (8, 10, 13, 20, 26, 29, 32, 37). Otherwise it is zero.

7. The alpha half-life in the unknown sample. Usually no more than one isotope accounts for over 90 % of the alpha decay rate and the error in that half-life becomes the error for this category. If the principal isotope for the two samples is the same, or if the mass ratio was determined by measuring the relative thermal fission rates, the error in the ratio is zero. The cor-

relation is 1.0 for all measurements with samples having the same principal alpha emitter. There is complete correlation within each of the following groups of measurements: (1, 2, 3, 4, 5, 6), (7, 8, 10, 12, 13, 29, 320, (15, 16, 17, 18, 19, 20, 27, 30, 32), (21, 22, 23, 25, 26), (33, 34), (35, 36, 37, 38, 40, 41). The errors in the alpha half-lives were taken from the literature as described in ref. 1.

8. The alpha half-life in the reference sample. This is the same as in section 7. There is complete correlation between all measurements involving reference samples U-235 5-2, 5-3, SST-5 and SST-8 since their principal alpha emitter is ^{234}U. Another group is formed by reference samples U-235-6, 10 and 14 since their principal alpha emitter is ^{233}U.

9. Error in the thermal fission ratio.

a. Random error. The correlation is zero for all measurements.

b. Error in the thermal fission cross section ratio. This was assumed to be 0.5 % for all cases where the thermally fissionable isotopes were not the same[1]. Otherwise it was zero. The correlation is 1.0 for measurements 9, 11, and 14. For all others it is zero.

10. Error in the prompt neutron scattering correction. This was assumed to be 30 % of the calculated correction but not less than 0.2 % of the measured fission cross section ratio. The correlation is 1.0 for all measurements of a particular ratio and 0.5 for all other cases.

RESULTS

The errors listed in Table II and the correlation information in the text were used according to eqs. (4) and (6) to produce the correlation matrix shown in Table III. Average values, shown in Table IV, of the fission cross section ratios, their standard deviations and χ^2 were calculated with eqs. (2), (3) and (8) respectively. In all cases χ^2 is less than, or not much greater than, 1.0 so no upward adjustment in the random error is necessary.

The off diagonal elements of the correlation matrix for the average fission cross section ratios were obtained with eq. (6) The complete matrix is shown in Table V.

For the ten isotopes used in these measurements there are 45 non-trivial and non-reciprocal ratios of which 9 were determined by measurement. The remaining 36 and their standard deviations were calculated using the average values in Table IV, the correlation information in Table V and eqs. (11) and (12). The results are listed in Table VI.

Fission cross sections for all these isotopes are given in ENDF/B-V[5]. Values at 14.74 MeV were obtained by linear interpolation and errors were calculated for those isotopes whose files included covariance information. The results are given in Table IV. The 46 possible fission cross section ratios were calculated and are compared with the results of this work in Table VI. Many of the errors are large and it is evident that the evaluators were not over-confident.

Column 6 of Table VI gives the ratio of this work to the ENDF/B-V values. It is evident that some large differences exist although they are within the errors assigned. Inspection of Table IV and VI shows that these differences could be greatly reduced if the evaluated cross sections of just three isotopes were decreased. These are: ^{230}Th - 13 %; ^{237}Np - 9.6 %; ^{239}Pu - 7.6 %. A 5 % decrease in the ^{236}U cross section would also help but that is becoming somewhat marginal. There is evidence for reducing some of these cross sections. In ref. 1 it was observed that the trend of recent measurements of the ^{237}Np and ^{239}Pu fission cross sections relative to ^{235}U was toward lower values. Furthermore the data base for the ^{230}Th evaluation was very limited and the error should be quite large.

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Table I. The Results of the Individual Cross Section Ratio Measurements.[a]

	Samples		Cross Section Ratio	Total Error (%)
1	Th-230-54	U-235 5-2	0.2958	2.2
2	Th-230-59	U-235 SST-5	0.2856	2.1
3	Th=230-54	U-235-14	0.2944	2.3
4	Th-232-30	U-235 5-2	0.1893	2.2
5	Th-232-31	U-235 5-2	0.1931	2.9
6	Th-232-34	U-235 SST-8	0.1915	2.2
7	U-233-1002	U-235 SST-5	1.134	1.3
8	U-233-1002	U-235-10	1.131	1.1
9 (th)	U-233-1002	U-235-10	1.141	1.2
10	U-233-1002	U-235-6	1.150	1.2
11 (th)	U-233-1002	U-235-6	1.127	1.2
12	U-233-1202	U-235 5-2	1.145	1.4
13	U-233-1402	U-234-14	1.119	1.2
14 (th)	U-233-1402	U-235-14	1.124	1.2
15	U-234-5	U-235 5-2	1.014	1.6
16	U-234-31	U-235 SST-5	1.012	1.5
17	u-234-32	U-235-14	0.991	1.4
18	U-234-4	U-235 5-3	0.993	1.4
19	U-234-4	U-235 SST-5	0.989	1.5
20	U-234-3	U-235-14	0.992	1.6
21	U-236-6	U-235 5-2	0.798	1.6
22	U-236-35	U-235 5-2	0.797	1.6
23	U-236-6	U-235-1	0.792	1.4
24 (th)	U-236-36	U-235-1	0.781	1.4
25	U-236-5	U-235 SST-5	0.794	1.6
26	U-236-4	U-235-14	0.793	1.4

Table I. (continued) The Results of the Individual Cross Section Ratio Measurements.[a]

		Samples		Cross Section Ratio	Total Error (%)
27		U-238-210	U-235 5-2	0.5902	1.8
28	(th)	U-238 8-2	U-235 5-2	0.5834	1.3
29		U-238-15	U-235-14	0.5818	1.3
30		U-238-213	U-235 SST-5	0.5960	1.8
31		U-238-60	U-235 SST-8	0.5783	2.4
32		U-238-9	U-235-6	0.5964	1.4
33		Np-237-76	U-235 SST-8	1.062	2.1
34		Np-237-79	U-235 5-2	1.059	1.6
35		Pu-239-267	U-235 SST-5	1.153	1.6
36		Pu-239-146	U-235 5-2	1.118	2.7
37		Pu-239-13	U-235-14	1.159	1.4
38		Pu-239-267	U-235 5-2	1.147	1.7
39	(th)	Pu-239-267	U-235 5-2	1.145	1.5
40		Pu-242-49	U-235 5-2	0.968	1.4
41		Pu-242-49	U-235 SST-5	0.964	1.4
42	(th)	Pu-242-49	U-245 SST-5	0.968	1.3

[a]Those measurements where the sample mass ratio was determined by measuring the relative thermal fission rate are indicated by (th).

Table II. Error Table.

Error Components

	1.	2.a.	2.b.	2.c.	3.a.	3.b.	3.c.	4.a.	4.b.	4.c.	5.	6.	7.	8.	9.b.	9.b.	10.
1	0.65	1.00	0.90	0.30	0.46	0.98	0.30	0.62	0.50	0.30	0.00	0.20	0.39	0.12	0.00	0.00	0.67
2	0.70	1.00	0.76	0.30	0.34	0.98	0.30	0.38	0.44	0.30	0.00	0.40	0.39	0.12	0.00	0.00	0.64
3	0.68	1.00	0.90	0.30	0.46	0.98	0.30	0.63	0.64	0.30	0.00	0.40	0.39	0.12	0.00	0.00	0.64
4	0.67	1.00	0.30	0.30	0.74	1.12	0.30	0.62	0.50	0.30	0.40	0.20	0.39	0.12	0.00	0.00	0.67
5	0.67	1.00	0.30	0.30	1.48	1.64	0.30	0.64	0.64	0.30	0.40	0.40	0.39	0.12	0.00	0.00	0.67
6	0.66	1.00	0.30	0.30	0.74	1.10	0.30	0.62	0.50	0.30	0.40	0.20	0.39	0.12	0.00	0.00	0.67
7	0.69	0.00	0.30	0.30	0.32	0.36	0.30	0.38	0.44	0.30	0.00	0.40	0.13	0.12	0.00	0.00	0.25
8	0.67	0.00	0.30	0.30	0.32	0.36	0.30	0.32	0.32	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.25
9 (th)	0.67	0.00	0.30	0.30	0.16	0.18	0.00	0.16	0.16	0.00	0.00	0.00	0.00	0.00	0.65	0.50	0.25
10	0.66	0.00	0.30	0.30	0.38	0.36	0.30	0.26	0.40	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.25
11 (th)	0.66	0.00	0.30	0.30	0.16	0.18	0.00	0.13	0.20	0.00	0.00	0.00	0.00	0.00	0.65	0.50	0.25
12	0.66	0.00	0.30	0.30	0.34	0.58	0.30	0.62	0.50	0.30	0.00	0.20	0.13	0.12	0.00	0.00	0.25
13	0.67	0.00	0.30	0.30	0.36	0.28	0.30	0.36	0.38	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.25
14 (th)	0.67	0.00	0.30	0.30	0.18	0.14	0.00	0.18	0.19	0.00	0.00	0.00	0.00	0.00	0.61	0.50	0.25
15	0.63	0.75	0.30	0.30	0.46	0.60	0.30	0.62	0.50	0.30	0.00	0.20	0.00	0.00	0.00	0.00	0.20
16	0.63	0.75	0.30	0.30	0.32	0.42	0.30	0.38	0.44	0.30	0.00	0.40	0.00	0.00	0.00	0.00	0.20
17	0.65	0.75	0.30	0.30	0.40	0.38	0.30	0.36	0.38	0.30	0.00	0.00	0.12	0.13	0.00	0.00	0.20
18	0.66	0.75	0.30	0.30	0.40	0.30	0.30	0.32	0.26	0.30	0.00	0.20	0.00	0.00	0.00	0.00	0.20
19	0.67	0.75	0.30	0.30	0.40	0.30	0.30	0.38	0.44	0.30	0.00	0.40	0.00	0.00	0.00	0.00	0.20
20	0.67	0.75	0.30	0.30	0.36	0.80	0.30	0.36	0.38	0.30	0.00	0.00	0.12	0.13	0.00	0.00	0.20
21	0.64	0.72	0.30	0.30	0.48	0.30	0.30	0.62	0.50	0.30	0.00	0.20	0.14	0.12	0.00	0.00	0.39
22	0.64	0.72	0.30	0.30	0.36	0.40	0.30	0.62	0.50	0.30	0.00	0.20	0.14	0.12	0.00	0.00	0.39
23	0.65	0.72	0.30	0.30	0.48	0.30	0.30	0.34	0.32	0.30	0.00	0.20	0.14	0.12	0.00	0.00	0.39
24 (th)	0.65	0.72	0.30	0.30	0.24	0.24	0.00	0.17	0.16	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.39
25	0.68	0.72	0.30	0.30	0.46	0.52	0.30	0.38	0.44	0.30	0.00	0.40	0.14	0.12	0.00	0.00	0.39
26	0.68	0.72	0.30	0.30	0.38	0.26	0.30	0.36	0.38	0.30	0.00	0.00	0.14	0.13	0.00	0.00	0.39

Table II. (continued) Error Table.

	Error Components																
	1.	2.a.	2.b.	2.c.	3.a.	3.b.	3.c.	4.a.	4.b.	4.c.	5.	6.	7.	8.	9.b.	9.b.	10.
27	0.67	0.66	0.30	0.30	0.76	0.48	0.30	0.62	0.50	0.30	0.40	0.20	0.00	0.00	0.00	0.00	0.61
28 (th)	0.67	0.66	0.30	0.30	0.30	0.20	0.00	0.31	0.25	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.50
29	0.46	0.66	0.30	0.30	0.36	0.24	0.30	0.36	0.38	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.48
30	0.46	0.66	0.30	0.30	0.48	0.98	0.30	0.38	0.44	0.30	0.40	0.40	0.00	0.00	0.00	0.00	0.61
31	0.67	0.66	0.30	0.30	1.22	1.24	0.30	0.64	0.64	0.30	0.00	0.40	0.11	0.12	0.00	0.00	0.50
32	0.46	0.66	0.30	0.30	0.38	0.46	0.30	0.26	0.40	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.48
33	0.59	0.60	0.30	0.30	0.94	1.08	0.30	0.64	0.64	0.30	0.00	0.40	0.47	0.12	0.00	0.00	0.20
34	0.62	0.60	0.30	0.30	0.44	0.48	0.30	0.62	0.50	0.30	0.00	0.20	0.47	0.12	0.00	0.00	0.20
35	0.64	0.28	0.76	0.30	0.32	0.82	0.30	0.38	0.44	0.30	0.00	0.40	0.13	0.12	0.00	0.00	0.20
36	0.67	0.28	1.82	0.30	0.50	1.40	0.30	0.62	0.30	0.30	0.00	0.20	0.13	0.12	0.00	0.00	0.20
37	0.67	0.28	0.50	0.30	0.37	0.64	0.30	0.36	0.38	0.30	0.00	0.00	0.13	0.12	0.00	0.00	0.20
38	0.60	0.28	0.76	0.30	0.32	0.82	0.30	0.62	0.50	0.30	0.00	0.20	0.13	0.12	0.00	0.00	0.20
39 (th)	0.60	0.28	0.76	0.30	0.16	0.41	0.00	0.31	0.25	0.00	0.00	0.00	0.00	0.00	0.70	0.50	0.20
40	0.69	0.10	0.30	0.30	0.32	0.54	0.30	0.62	0.50	0.30	0.10	0.20	0.13	0.12	0.00	0.00	0.20
41	0.71	0.10	0.30	0.30	0.32	0.54	0.30	0.38	0.44	0.30	0.10	0.40	0.13	0.12	0.00	0.00	0.20
42 (th)	0.71	0.10	0.30	0.30	0.16	0.27	0.00	0.19	0.22	0.00	0.10	0.00	0.00	0.00	0.70	0.50	0.20

Table III. The Correlation Matrix for the Experimental Data.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	100																									
2	46	100																								
3	72	49	100																							
4	49	34	34	100																						
5	26	29	40	27	100																					
6	50	34	34	51	28	100																				
7	23	46	29	19	19	19	100																			
8	25	24	25	20	17	20	14	100																		
9	24	24	24	20	15	20	13	67	100																	
10	26	25	25	21	16	21	14	41	27	100																
11	24	24	24	20	15	20	13	26	37	27	100															
12	44	22	23	39	14	39	13	15	15	16	53	100														
13	26	25	25	21	16	21	14	17	17	18	17	16	100													
14	25	24	25	20	15	20	14	17	34	17	34	15	70	100												
15	57	35	36	49	22	50	20	21	20	21	20	47	21	21	100											
16	40	44	44	31	28	32	51	23	22	24	22	21	24	23	35	100										
17	41	40	41	32	25	33	22	24	23	24	23	21	46	33	36	40	100									
18	44	41	42	35	26	35	23	25	24	25	24	24	25	24	39	42	43	100								
19	40	59	44	31	28	31	51	23	22	23	22	21	23	23	35	65	40	42	100							
20	37	36	37	29	22	29	20	21	21	22	21	19	41	29	32	36	54	39	36	100						
21	59	36	37	51	23	52	21	21	21	22	21	49	22	21	61	61	34	35	31	34	100					
22	59	36	37	51	23	52	21	22	21	22	21	49	22	21	34	34	37	38	52	38	64	100				
23	40	39	40	32	25	33	23	23	23	24	23	21	24	23	35	35	38	40	35	57	54	39	100			
24	41	40	41	33	25	33	22	24	24	25	24	22	25	24	38	38	42	41	40	40	35	39	42	100		
25	36	55	41	29	26	30	48	21	21	22	21	19	22	21	34	34	37	38	58	38	32	36	39	38	100	
26	40	39	40	32	25	32	22	24	23	24	23	21	46	33	32	32	35	36	31	51	35	39	42	43	38	100

Table III. (continued) The Correlation Matrix for the Experimental Data.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
27	52	47	31	45	20	45	18	19	18	19	18	42	19	19	52	29	30	32	29	27	54	54	31	31	27	30
28	42	41	42	34	26	34	23	25	24	26	24	22	26	25	35	39	40	42	39	36	36	36	40	41	36	40
29	43	41	42	34	27	34	23	25	25	26	25	23	26	25	36	39	60	42	40	54	36	36	40	41	36	60
30	32	48	36	26	23	26	42	19	19	19	19	17	19	19	26	51	30	31	35	27	27	27	30	31	48	30
31	24	27	41	19	31	20	19	14	14	14	14	13	14	14	20	26	22	23	26	20	21	21	23	23	24	22
32	41	40	41	33	26	33	23	24	24	46	44	22	25	24	34	38	39	40	37	35	35	35	38	40	35	39
33	23	26	43	18	17	19	19	13	13	14	13	12	14	13	20	27	23	24	27	20	20	20	22	22	25	22
34	52	30	31	46	19	46	17	18	17	18	17	45	18	18	56	29	30	33	29	27	58	58	31	30	26	29
35	35	52	39	28	25	28	46	20	20	20	19	18	20	20	30	57	34	35	39	31	30	30	33	33	52	33
36	57	44	34	48	27	48	24	26	25	26	25	40	26	25	57	43	45	48	43	40	57	57	43	43	38	42
37	31	30	30	24	19	24	17	18	17	18	17	16	40	27	26	29	49	31	29	44	26	26	29	30	26	48
38	54	33	34	47	21	47	19	20	19	20	19	43	20	19	57	32	33	36	32	30	58	59	34	32	29	32
39	32	31	31	25	19	25	17	18	18	19	18	16	19	18	27	30	31	32	30	28	27	27	30	30	27	30
40	46	21	21	41	13	41	12	12	12	12	12	44	12	12	51	20	20	23	19	18	53	53	22	20	18	20
41	22	38	22	18	14	18	36	13	12	13	12	11	13	13	18	41	21	22	20	19	19	19	21	21	39	21
42	23	30	23	18	14	18	24	14	13	14	13	12	14	13	19	31	22	23	21	20	20	20	21	22	29	22

Table III. (continued) The Correlation Matrix for the Experimental Data.

	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
27	100															
28	32	100														
29	32	50	100													
30	30	39	55	100												
31	18	28	28	26	100											
32	31	48	48	37	27	100										
33	17	23	23	21	35	22	100									
34	49	30	55	22	17	29	24	100								
35	25	34	34	45	19	33	19	26	100							
36	48	43	58	32	24	42	25	52	38	100						
37	22	43	50	22	17	29	17	22	25	34	100					
38	50	33	33	24	19	32	19	54	60	39	26	100				
39	23	31	31	23	17	30	17	23	54	35	24	67	100			
40	45	21	21	16	12	20	12	50	18	23	15	49	31	100		
41	16	22	22	16	13	21	12	16	18	23	16	18	16	39	100	
42	17	23	23	17	13	22	12	16	18	24	17	18	29	25	65	100

Table IV. The Weighted Averages of the Fission Cross Section Ratio Measurements and the Derived Fission Cross Sections Compared with ENDF/B-V.

	σ Ratio	Total Error (%)	$\aleph^2$	σ^a (b)	σ ENDF/B-V (b)	Error[b] (%)
$^{230}Th/^{235}U$	0.2905	1.8	1.26	0.610	0.690	13.0
$^{232}Th/^{235}U$	0.1910	1.8	0.25	0.401	0.393	----
$^{233}U/^{235}U$	1.134	0.7	1.08	2.382	2.299	----
$^{234}U/^{235}U$	0.997	1.1	1.11	2.095	2.113	----
$^{236}U/^{235}U$	0.791	1.0	0.43	1.662	1.745	----
$^{238}U/^{235}U$	0.587	1.0	1.27	1.233	1.193	6.6
$^{237}Np/^{235}U$	1.060	1.4	0.02	2.227	2.441	15.0
$^{239}Pu/^{235}U$	1.154	1.1	0.58	2.420	2.607	11.9
$^{242}Pu/^{235}U$	0.967	1.0	0.08	2.032	2.016	7.9

[a]The fission cross section was obtained from the measured ratio using the ENDF/B-V value for the U-235 fission cross section (2.101 ± 6 %).

[b]Errors are given for ENDF/B-V fission cross sections for those cases where covariance information is included in the file.

Table V. The Correlation Matrix for the Fission Cross Section Ratios.

α		Ratio	Err. (%)	1	2	3	4	5	6	7	8	9
1	Th-230/U-235	0.290	1.8	100								
2	Th-232/U-235	0.191	1.8	57	100							
3	U -233/U-235	1.134	0.7	58	48	100						
4	U -234/U-235	0.997	1.1	69	60	62	100					
5	U -236/U-235	0.791	1.0	71	59	64	78	100				
6	U -238/U-235	0.587	1.0	68	58	58	73	73	100			
7	Np-237/U-235	1.060	1.4	53	51	41	53	53	56	100		
8	Pu-239/U-235	1.154	1.1	52	43	50	59	62	59	36	100	
9	Pu-242/U-235	0.967	1.0	42	40	37	44	43	39	37	35	100

Table VI. A List of All Measured and Derived Fission Cross Section Ratios.[a]

	This Work		ENDF/B-V		(Exp./ENDF)
	Ratio	Error	Ratio	Error[b]	
Th-232/Th-230	0.658	1.7	0.570	---	1.154
U -233/Th-230	3.904	1.5	3.332	---	1.172
U -234/Th-230	3.432	1.3	3.062	---	1.121
U -235/Th-230	3.442	1.8	3.045	---	1.130
U -236/Th-230	2.723	1.3	2.529	---	1.077
U -238/Th-230	2.021	1.3	1.729	---	1.169
Np-237/Th-230	3.649	1.6	3.538	---	1.031
Pu-239/Th-230	3.972	1.5	3.778	---	1.051
Pu-242/Th-230	3.305	1.6	2.922	---	1.139
U -233/Th-232	5.937	1.6	5.850	---	1.015
U -234/Th-232	5.220	1.4	5.337	---	0.978
U -235/Th-232	5.236	1.8	5.346	14.3	0.979
U -236/Th-232	4.141	1.4	4.440	---	0.933
U -238/Th-232	3.073	1.5	3.036	14.6	1.012
Np-237/Th-232	5.549	1.6	6.211	19.8	1.054
Pu-239/Th-232	6.042	1.7	6.634	17.6	0.911
Pu-242/Th-232	5.063	1.7	5.130	15.2	0.987
U -234/U -233	0.879	0.9	0.919	---	0.808
U -235/U -233	0.882	0.7	0.914	---	0.965
U -236/U -233	0.698	0.8	0.759	---	0.920
U -238/U -233	0.518	0.8	0.519	---	0.998
Np-237/U -233	0.935	1.3	1.062	---	0.880
Pu-239/U -233	1.018	1.0	1.134	---	0.900
Pu-242/U -233	0.853	1.0	0.877	---	0.973
U -235/U -234	1.003	1.1	0.994	---	1.009
U -236/U -234	0.793	0.7	0.826	---	0.960
U -238/U -234	0.589	0.8	0.565	---	1.042
Np-237/U -234	1.063	1.2	1.155	---	0.920
Pu-239/U -234	1.157	1.0	1.234	---	0.938
Pu-242/U -234	0.970	1.1	0.954	---	1.017
U -236/U -235	0.791	1.0	0.831	---	0.952
U -238/U -235	0.587	1.0	0.568	8.9	1.033
Np-237/U 235	1.060	1.4	1.162	16.2	0.912
Pu-239/U -235	1.154	1.1	1.241	13.3	0.929
Pu-242/U -235	0.967	1.0	0.960	9.9	1.007

Table VI. (continued) A List of All Measured and Derived Fission Cross Section Ratios.[a]

	This Work		ENDF/B-V		(Exp./ENDF)
	Ratio	Error	Ratio	Error[b]	
U -238/U -236	0.742	0.7	0.684	---	1.085
Np-237/U -236	1.340	1.2	1.399	---	0.958
Pu-239/U -236	1.459	0.9	1.494	---	0.977
Pu-242/U -236	1.222	1.1	1.155	---	1.058
Np-237/U -238	1.805	1.2	2.046	16.4	0.882
Pu-239/U -238	1.966	1.0	2.185	13.6	0.900
Pu-242/U -238	1.647	1.1	1.690	14.3	0.975
Pu-239/Np-237	1.089	1.4	1.068	19.2	1.020
Pu-242/Np-237	0.912	1.4	0.826	17.0	1.104
Pu-239/Pu-242	1.191	1.2	1.293	16.6	0.921

[a]The experimental values from this work are underlined.

[b]Errors are given for the ENDF/B-V values for those cases where covariance information is included in the files.