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Review of the Current Status of the U-238, Np-237 and Th-232 Fission Cross Sections

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Abstract

The experimental fission cross-section data of U-238, Np-237 and Th-232, published up to the end of 1970, are reviewed and analyzed between their respective thresholds and 20.0 MeV. The results of a statistical analysis of the available data, performed with a weighted Least-squares Orthogonal Polynomial Fitting computer programme are presented in the form of point-wise cross-section values together with their uncertainties, and in the form of graphs of the fitted curves with an indication of a region of 95% statistical confidence level. An estimate of the fission spectrum weighted average cross-sections and their respective uncertainties is also given.

요 약

1970년 말까지 보고된 U-238, Np-237 및 Th-232의 고속중성자에 대한 핵분열단면적 및 그 실험오차를 조사분석하여 최소자승직교다항식적합법에 의하여 단면적의 최적치와 95%신뢰도에 대응하는 오차범위를 계산하고 이 결과를 사용하여 분열스펙트럼에 대한 평균단면적치를 추정하였다.

I. Introduction

In recent years, a great deal of effort has been devoted to the development of techniques to measure neutron fission spectra, differential fast neutron spectra, and fast neutron fluences in diverse areas of research (Refs. 1—6). One of the established methods to measure fast neutron flux and spectra is the application of threshold detectors based on threshold reactions such as (n, p), (n, α), (n, 2n), (n, f) and (n, n′). In all of these and related applications an accurate knowledge of the energy-dependent reaction cross sections, as well as of the spectrum-weighted integral cross sections, is of basic importance.

The object of this work has been to attempt a thorough statistical evaluation of existing experimental fast neutron fission cross sections for Th-232, Np-237 and U-238 in the energy range from threshold up to 20 MeV. No consideration has been given to the sub-threshold

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region, nor has the threshold itself been specifically investigated.

Numerous compilations and recommendations of the considered cross sections have been made in the past. Two factors, however, justify the current review: one is the availability of new data which have not been considered in earlier reviews and evaluations, the other is the derivation of statistical confidence levels with due account of the associated data uncertainties. It is hoped that justice has been done to both of these points: considering in this review most known existing data, and introducing the use of computerized statistical fitting procedure, in the derivation of the final results.

The two principal features of this study are the treatment of the experimental data used as input for the analysis, and the method used to analyze the data and their related uncertainties. With regard to the data, in as many cases as was feasible, most sets have been renormalized to Davey's 1968 evaluation of the U-235 fission cross section (Ref. 13), eliminating thus, as far as possible, those discrepancies arising from differences in normalization. The second emphasis of this work has been placed on the statistical fitting of the experimental data by means of a weighted Least-Squares Orthogonal Polynomial Fitting Program (Refs. 19, 20) yielding fitted excitation curves together with an estimate of their point-wise as well as regional uncertainties based on a 95 precent confidence level.

Although statistical fitting programmes, such as the one used in this analysis, are powerful tools for efficient and rapid processing of experimental data, one must realize that a statistical approach dealing not exclusively with statistical errors sometimes disregards and often does not do justice to the underlying physics. Furthermore, these methods treat the uncertainties attached to the data, whether their origin is systematic or random, in a purely statistical way.

The situation is aggravated more in that the data, and specifically the uncertainties assigned to the data, are not always specified by the authors as being either systematic or statistical, at best one single error is usually given. Thus, the results given in this report, in particular the uncertainties attached to the recommended values, must be viewed in the light of these considerations.

2. Review of the considered experimental data.

The sets of experimental data collected for this review were obtained from two sources. As part of the initial survey, the U. S. National Neutron Cross Section Center (at Brookhaven) supplied an up-to-date (April 1970) selected retrieval from the SCISRS files; this initial effort was supplemented by a literature search with the help of CINDA-69 which resulted in the collection of those cross section data which had appeared in the published literature(Refs. 22-54) up to the end of 1970.

In the first phase of the review all collected data sets were classified according to measurement type, normalization and completeness of information, into the following four categories:

(1) Absolute cross section measurements. Unmodified values used in this review.

(2) Measured cross-section ratios which were converted to the cross-section values used in this review by applying recognized standard cross-sections.

(3) Cross-section shape measurements which were normalized to a reference standard to obtain the values used in this review.

(4) Other cross-section measurements, for which information on normalization was

ambiguous, or data which had to be read from curves and for which no error estimate was given.

Cross-sections which fall under category 1 have been considered here to be the "best" or most reliable; in all of these cases the original values were used for the input. In determining the cross-sections from measured cross-section ratios (category 2), or in re-normalizing the data in category(3) to more recent and currently accepted reference cross-sections, the standard which was found to be most widely used, or which in the final analysis was the basis of the recommended values, is the U-235 fission cross-section. Although it is beyond the scope of this review to give a detailed analysis of the basic U-235 (n, f) cross-section, a current appraisal of the various recommended sets of the evaluated U-235 fission cross-sections (Refs. 4, 10-13, 15, 16, 22) in the energy range under consideration was necessary; these are given in graphical form in Figure 1.

Of these evaluated sets, Davey's recommended values (Ref. 13) up to 10 MeV, have been considered during the last few years as the most reliable reference data. These data have recently been substantiated by the revised Henkel and Nobles data and have also been adopted by Alter and Dunford (Ref. 16) in their re-evaluation of the U-235 neutron cross-section. Schmidt's recent evaluation (Ref. 22) also shows a closer agreement with Davey's values up to 1 MeV, however Schmidt's recommended curve for the energy range above 10 MeV appears to be more reasonable than the extrapolated values given by Alter and Dunford. In the present review, the U-235 (n, f) cross-sections used as standard are based on Alter and Dunford's (Ref. 16) values up to 10 MeV and on Schmidt's recommended curve above 10 MeV.

Most data sets which fall in category (4) were not used in this review primarily because of the lack of experimental documentation. One of the exceptions has been the use of Henkel's 1957 values of the Th-232 fission cross-section which were reported in LA-2122 (Ref. 53) and included in the 1958 edition of BNL-325. These data were measured at a very high energy resolution: unfortunately the numerical data of this experiment were not available in tabular form, and the data had to be read from Henkel's curve in order to reproduce the highly resolved structure in the beginning of the first plateau, between 1.5 and 2.0 MeV. For the purpose of this review 88 points at 0.1 MeV intervals were read from the curve and a 5% uncertainty was assumed, taking into consideration the error of the U-235 standard cross-section used in this experiment, which is presumably Diven's 1953 value of the U-235 $\sigma(n, f) = 1.269 \pm 3.5\%$ at 1.25 MeV.

The cross-section data error plays an essential part in assigning the statistical weight to each data input point, and in the subsequent treatment of these data by the fitting program. Because of the widely differing modes of error analysis presented by the authors of the experiments considered here, it has not been possible to separate systematic from statistical errors; consequently what has been used as input in this study are the overall errors assigned by the experimenters wherever these were given. In those cases where the data were normalized or re-normalized, the effect of error propagation, which stemmed from the uncertainties of the standards used in the initial normalization, could not be taken into account in all cases because of lack of information, and the errors originally given for the measured data were transferred to the revised cross-section values.

The data sets used in the review of the

U-238, Np-237 and Th-232 fission cross-sections are given in graphical form in Figures 2, 3 and 4 respectively. In summary, this survey of available data has yielded 111 U-238 (n, f) data points, 264 Np-237 (n, f) data points, and 153 Th-232 (n, f) data points which were used as input to the fitting program described in Section III. A brief description of each individually considered data set is given below for each of the three isotopes.

Data sets used for the U-238 (n, f) review

1) Hansen, McGuire and Smith (1968)(Refs. 24, 25). 45 data points between 1.0 and 22.0 MeV. The data used are those given by Smith, see Reference 24. Error given by the authors ranges between 3% and 6%. Measured relative to (n, p).

2) Kalinin and Pankratov (1958) (Refs. 26, 28). 7 data points between 3.1 and 6.3 MeV. Data read from curve. Assigned uncertainty of 7% by authors. Absolute measurement.

3) Emma et al. (1965) (Ref. 37). 7 data points between 1.8 and 4.5 MeV. Original data used. 5% uncertainty given by the authors. Shape measurement.

4) Adams, Batchelor and Green (1961)(Ref. 36). 14 data points between 12.7 and 19.4 MeV. Relative measurement normalized at 14 MeV to Moat's (1957) 1.13 barn value. Original data used. Statistical error of ~4% given by the authors.

5) White and Warner (1967) (Ref. 32). Three data points at 2.25, 5.4 and 14.1 MeV. Original measurement normalized to the U-235 fission cross sections as given by Stehn(1965). Renormalized for this work to Alter and Dunford's and Schmidt's U-235(n, f) values. 2% standard deviation of the cross section given by author.

6) Stein, Smith and Smith (1968) (Ref. 34). 14 data points between 1.5 and 5.00 MeV. U238/U235 ratio measurement normalized for this review to Alter and Dunford's data. 2.2% absolute cross section error given by authors.

7) Lamphere (1956) (Ref. 35)
6 data points between 0.5 and 3.0 MeV (supplemented by 10 values read from curve given in KFK 120/I). Ratio measurement re-normalized for this review to Alter and Dunford's values. Total uncertainty of deduced cross-section is ~5.2%.

8) Pankratov et al. (1960) (Ref. 27)
16 data points between 10.6 and 21.5 MeV. Data measured relative to U-238 σ_f at 14 MeV Values read from curve and re-normalized in this work to Moat's (1958) value of 1.13 barns at 14 MeV. Error as given by the author is ±5%.

9) Pankratov (1963) (Ref. 28)
25 data points between 3.4 and 21.9 MeV. Data measured were normalized to the U-238 σ_f at 3.4 MeV, as given in Pankratov 1960. Includes corrected 1958 data by Kalinin and Pankratov between 3.0 and 8.5 MeV. Data read from curve and re-normalized to Moat's (1958) value of 1.13 barns at 14 MeV. Error as given by the authors is ±5%.

Data sets used for the Np-237(n, f)review

1) Otroshchenko and Shigin (1961)(Refs. 42, 43) 24 data points between 0.012 and 1.5 MeV. Data read from curve. Cross-section errors as given by authors range from 3% to 6%.

2) Kalinin and Pankratov (1958) (Refs. 26, 28) 13 data points between 2.5 and 8.3 Mev. Data read from curve. Cross-section errors as given by authors are about 7%, Relative measurement normalized to measured absolute value.

3) Protopopov, et al. (1958) (Ref. 52)
One data point at 14.6 MeV. Error is 8.3%. Absolute measurement.

4) White, Hodgkinson and Wall (1965)(Ref.

39) 5 data points between 0.04 and 0.505 MeV. Relative measurement. Data was renormalized to Alter and Dunford's values for this review. Combined error quoted by authors is around 8%.

5) Brown et al. (Pommard) (1970) (Ref. 46) 161 data points between 0.1 and 2.85 MeV have been used in this review. Data is normalized by authors to Davey's 1968 (Ref. 13) U-235 (n, f) evaluation. Error ranges between 7% aed 25%, centres around 10%.

6) Stein, Smith and Smith (1968) (Ref. 34) 12 data points between 1.0 and 4.5 MeV. Np-237/U-235 fission ratio measurement normalized to Alter and Dunford's U-235 (n, f) values. Ratio measurement error of 2.6% quoted by author was used for the normalized values used in this review.

7) White and Warner (1967) (Ref. 32) 4 data points between 1.0 and 14.1 MeV. Np-237/U-235 fission ratio measuremeat originally normalized to Stehn's (1965) U-235 values, re-normalized to Alter and Dunford's and Schmidt's U-235 (n, f) values for this review. Ratio measurement error of 3-4% was used for the normalized values used in this report.

8) Stein, Smith and Grundl (1968) (Ref. 33) 7 data points between 1.5 and 4.5 MeV. Np-237/U-238 fission ratio measurement normalized for this review to the U-238 (n, f) values obtained in this review. Ratio measurement error of 2.5% as given by authors has beed used for the normalized values.

9) Schmitt and Murray (1959) (Ref. 40) 30 data points between 0.90 and 8.0 MeV. Np-237/U-238 fission ratio measurement renormalized for this review to the U-238 (n, f) values obtained in this review. Estimated combined error used in this review is 7%.

10) Pankratov, Vlasov and Rybakov (1960) (Ref. 27) 17 data points between 9.6 and 21.8 MeV. Shape measurement. These data were normalized to Pankratov's later measurement (1963) (see next data reference) in the second plateau region (~9 to 14 MeV). Cross-section uncertainty as assigned by author is 5%.

11) Pankratov (1963) (Ref. 28) 24 data points between 3.4 and 21.7 MeV. Data measured relative to U-238 σ_f at 3.4 MeV, and renormalized for this review to Stein et al. (1968) values (see 8) above, Ref. 33) at 3.4 MeV. Cross-section uncertainty of 5% was assumed.

Data sets used for the Th-232 (n, f) review.

1) Behkami and Huizenga (1968) (Ref. 48) 3 data points at 1.2, 1.4 and 1.6 MeV. Th-232 cross-section determined from fission count relative to U-236 (n, f). Original data normalized for this review to Stein et al. (1968) U-236/U-235 fission ratio measurement using Davey's U-235 values. Combined error given by authors ranges between 7% and 10%.

2) Ermagambetov, Kuznetzov and Smirenkin (1967) (Ref. 49) 15 data points between 0.96 and 1.295 MeV. Measured relative to natural U uncertainty of 5% assigned by authors.

3) Babcock (1962) (Ref. 47) 5 data points between 13.0 and 18.0 MeV. Measurement relative to U-238 (original normalization values not given). Errors range from 4% to 22%.

4) Babcock (1961) (Ref. 54) 7 data points between 1.14 and 1.88 MeV. No experimental information available. Data from NNCSC, Brookhaven. Errors range from 8% to 35%.

5) Henkel (1957) (Ref. 53) 88 data points between 1.15 and 9.00 MeV. Orginal data normalized to Diven's (1953, LA-1336) U-235 fission cross-section at 1.25 MeV of 1.269 barns. Data from NNCSC, Brookhaven, were read from curve. Original tabulation not

available. A 5% error was assigned on the basis of error in original standard used.

6) Berezin et al. (1958) (Ref. 51)
One data point at 14.6 MeV. Absolute measurement. Approximate 5% error assigned by authors.

7) Protopopov, Selitskii and Soloviev (1958) (Ref. 52) One data point at 14.6 MeV. Absolute measurement. Approximate 5% error assigned by authors.

8) Kalinin and Pankratov (1958) (Ref. 26)
9 data points between 3.1 and 7.2 MeV. Relative measurement. Original data used. Error assigned by authors is 7%.

9) Pankratov, Vlasov and Rybakov (1960) (Ref. 27) 14 data points between 10.7 and 21.5 MeV. Relative measurement. Data renormalized to Pankratov 1963 values for this review. Error assigned by authors is 5%.

10) Pankratov (1963) (Ref. 28)
26 data points between 3.4 and 21.8 MeV. Data originally normalized by author to 0.135 barns at 3.4 MeV (BNL-325, 1957 Edition). Original data used. Error assigned by authors is 5%.

11) Rago and Goldstein (1967) (Ref. 50)
16 data points between 12.5 and 18.0 MeV. Th-232 fission cross-section determined relative to U-238 (n, f) cross-section. Original data was normalized to 1965 Barrall and McElroy U-238 fission cross-section. Data for this review were renormalized to U-238 (n, f) cross-section determined in this review. Combined error of 7% was assigned.

12) Uttley (1956) (Ref. 30)
One data point at 14.1 MeV. Ratio measurement. Original data based on U-238 σ_f value of 1.14 ± 0.07 barns at 14.1 MeV. Error is approximately 5%.

3. Fitting Procedure

The essential feature of the weighted least-squares polynomial fitting program used in this analysis is that it uses orthogonal polynomials which allows a high degree of fitting (up to degree 40) without excessive use of computer time. The orthogonality condition results in the matrix of the normal equations being diagonal, thereby avoiding the generation of the infinite Hilbert matrix. In the computation, the importance of each input data point, or weight W, is considered to be inversely proportional to either $(\triangle\sigma)^2$ (absolute weight) or $(\triangle\sigma/\sigma)^2$ (relative weight). The program also calculates statistical parameters which reflect the quality, or "goodness of fit" of a given degree of polynomial. This computer program was developed at the CERN European Organization for Nuclear Research, in Geneva (Refs. 19, 20) and adapted for nuclear data analysis at the IAEA, in Vienna.

In the actual fitting procedure, two subsequent operations are performed on the data. The first operation results in the determination of the optimum degree of fit which for the statistical F-distribution yields results within chosen confidence limits. The second operation yields point-wise values of the fitted function of the degree chosen on the basis of the first operation, and the statistical uncertainties of these point-wise values at the discrete values of the independent variable.

The point-wise uncertainties of the fitted function which the program calculates correspond to a chosen statistical confidence level of 95% of the estimated mean of the calculated point-wise values. These uncertainties, however, are attributed to the individual point-wise values only, and are not a measure of the width of the confidence region over the whole energy range. In order to obtain a quantitative measure of this confidence region, which will contain the whole fitted function uncertainty, at the discrete values as well as in the intervals, it is necessary to weight the calculated point-wise uncertainties at discrete values of the independent variable by a factor "f" which is a function of the degree of fit (k), and the statistical F-distribution factor (F) for a given level confidence. The parameters used in fitting the U-238 (n, f), Np-237 (n, f) and Th-232 (n, f) data are summarized in Table 1. All of the fitting operations are based on a statistical confidence level of 95% for the calculated accuracy of the fitted function. Also, in order to determine the optimum fitting parameters, the first run for each of the three considered reactions (not shown on Table 1) was a 40-degree fit, using relative errors(that is, where the weight of each point is inversely proportional to $\left(\frac{\triangle\sigma}{\sigma}\right)^2$ as part of the input.

Both the uncertainties of the input data as well as the frequency, or density, of input data play a determining role in the final specification of the accuracy of the fitted points. Of these two, the uncertainties of the input data, aside from the actual input data values, are probably the most sensitive, both from the physics point of view as well as in its interpretation in context of the mathematical treatment by the fitting progam. In view of the lack of experience gained so far in the application of this statistical fitting approach to the analysis of nuclear data, the liberties taken and assumptions made in the interpretation of the significance of the uncertainty input parameter must be considered at this stage of this review as being of an experimental nature. As an example, it was found that because of the variation of the data by several orders of magnitude in the energy range under consideration, it was desirable to convert the uncertainties of the input data (i. e. $\triangle\sigma$), which are in effect point-wise weighting factors in the mathematical operation, to relative errors, so as to achieve an equal importance of fitting throughout the considered energy range. In some cases, however, given energy regions,

Table 1. Fitting parameters

Reaction	E_n(MeV)		n	k	f	Remarks
	E_{min}	E_{max}				
U-238(n, f)	0.5	22.0	145	40	4.015	Data were weighted according to the inverse square of the absolute error for energy range $\leq$ 1.5MeV
				20	2.96	Data were weighted according to the inverse square of the relative error for energy range $\geq$1.5 MeV.
Np-237 (n, f)	0.07	22.0	298	32	3.45	Data were weighted according to the inverse square of the absolute error for energy range $\leq$0.7MeV
				26	3.17	Data were weighted according to the inverse square of the relative error for energy range $\geq$0.7 MeV.
Th-232 (n, f)			186	--	--	Full energy range could not be fitted
	0.8	8.0		30	3.55	Relative values of input
	7.0	22.0		19	3.015	uncertainties were used in both fits

Parameter descriptions: n=total number of input data points;
k=chosen degree of fit;
f=weighting factor to convert from ponit-wise to "continuous confidence region" uncertainty, defined as
$f=\sqrt{(k+1)\cdot F_{k+1\ n-k-1}}$

where F=statistical F—distribution factor for given degree of confidence.

such as the threshold regions of the U-238 and Np-237 cross-section, were fitted separately using the absolute error values in ordsr to reduce the resultant uncertainties of the fitted points and eliminate undesirable oscillations of the fitted function.

4. Discussion of the fitted results

The fitted point-wise results of the U-238, Np-237 and Th-232 fission cross-sections are tabulated in Tables 2-1, 2-2 and 2-3 respectively. The cross-section uncertainties, as given in these tables under the heading of "Delta Sigma", are "continuous confidence region" statistical uncertainties based on an assumed 95% statistical confidence level (i. e. point-wise uncertainties weighted by the factor f given in Table 1). The fitted curve and the "continuous confidence region", based on the 95%confidence level are shown on Figures 2, 3 and 4 for the three fission cross-sections together with the experimental data.

It is of interest to note that the width of the confidence region varies inversely with the density of input data points; this is particularly noticeable in the case of Th-232 (Fig. 4) in the energy region between 9.0 MeV and 13.0 MeV, where the spread of the data is 0.5 to 1.0 MeV, and the uncertainty of the fitted data reaches ±30%.

On the other hand, the width of the confidence region appears to be unreasonably narrow in some cases, and is not representative of the uncertainties implied by the input data error-bars. This is particularly noticeable in the 0.5 MeV to 9.0 MeV range of the Np-237 fission cross-section (Fig. 3) in the 12.0 MeV to 20.0 MeV range of the U-238 fission cross-section (Fig. 2) and also in the 2.0 MeV to 5.5 MeV range of the U-238 curve. Hand-drawn envelopes shown by dashed curves define the areas in question in these three cases.

As more accurate measurements with higher energy resolution began to be performed, the

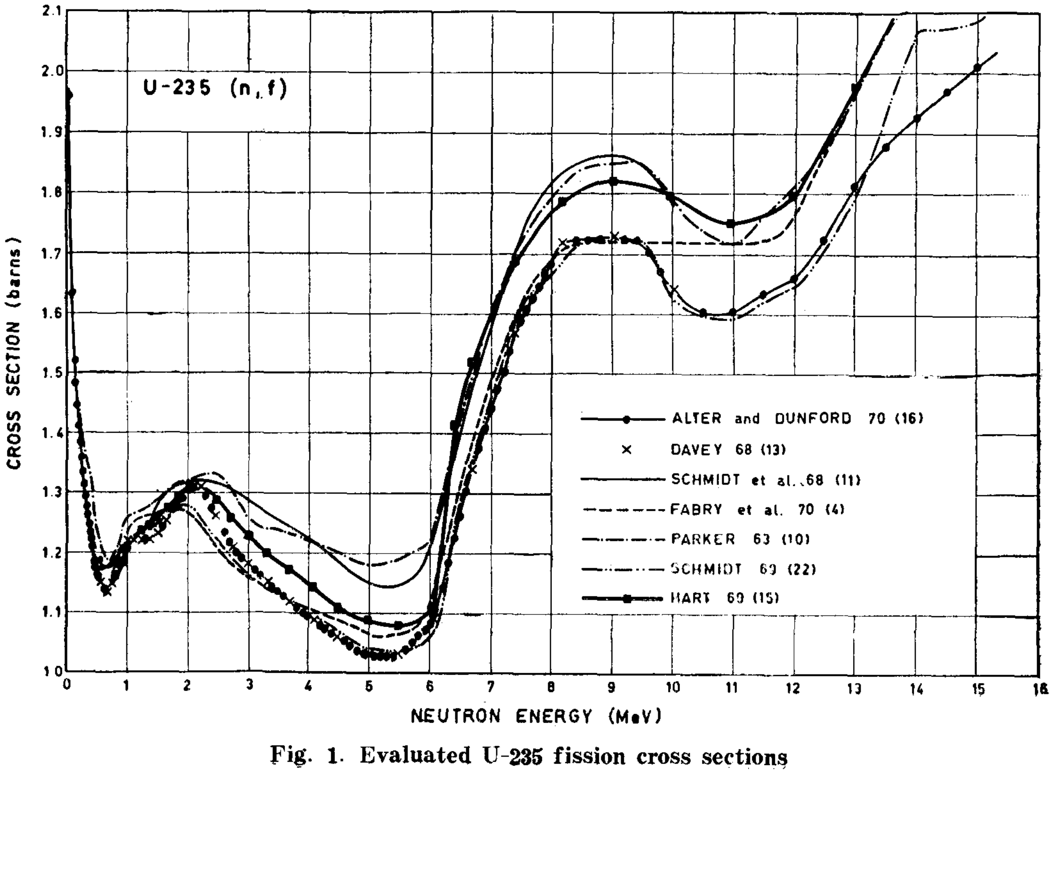

Fig. 1. Evaluated U-235 fission cross sections

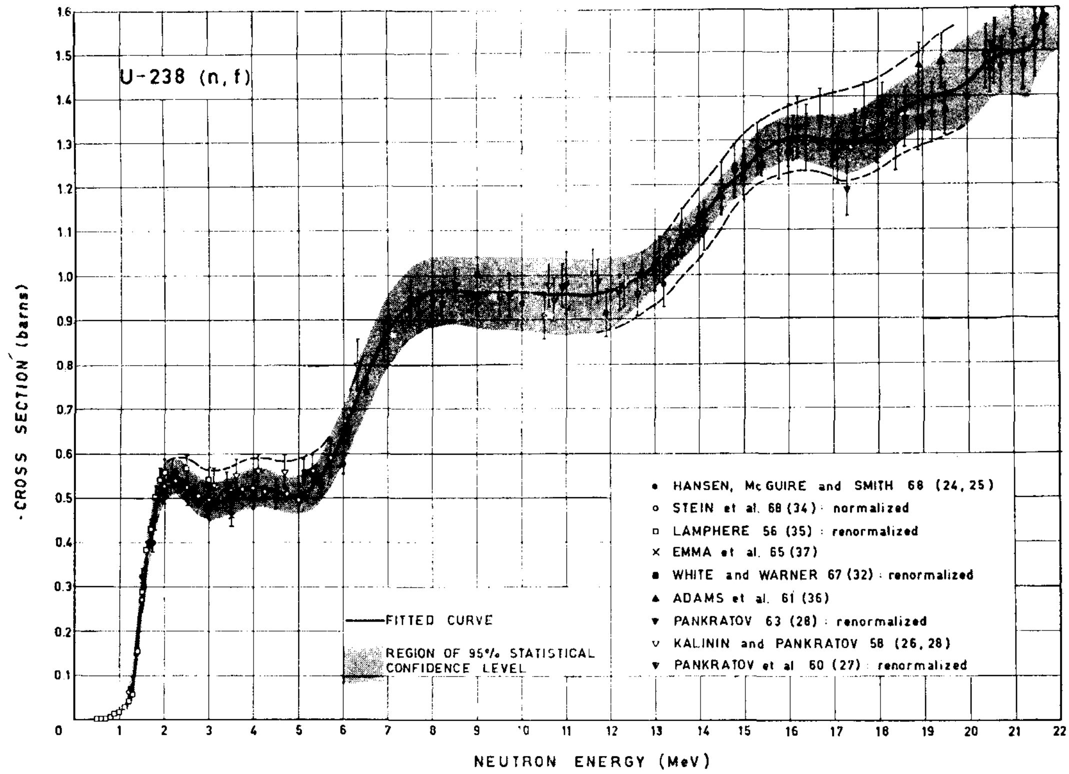

Fig. 2. U-238 (n, f) excitation curve

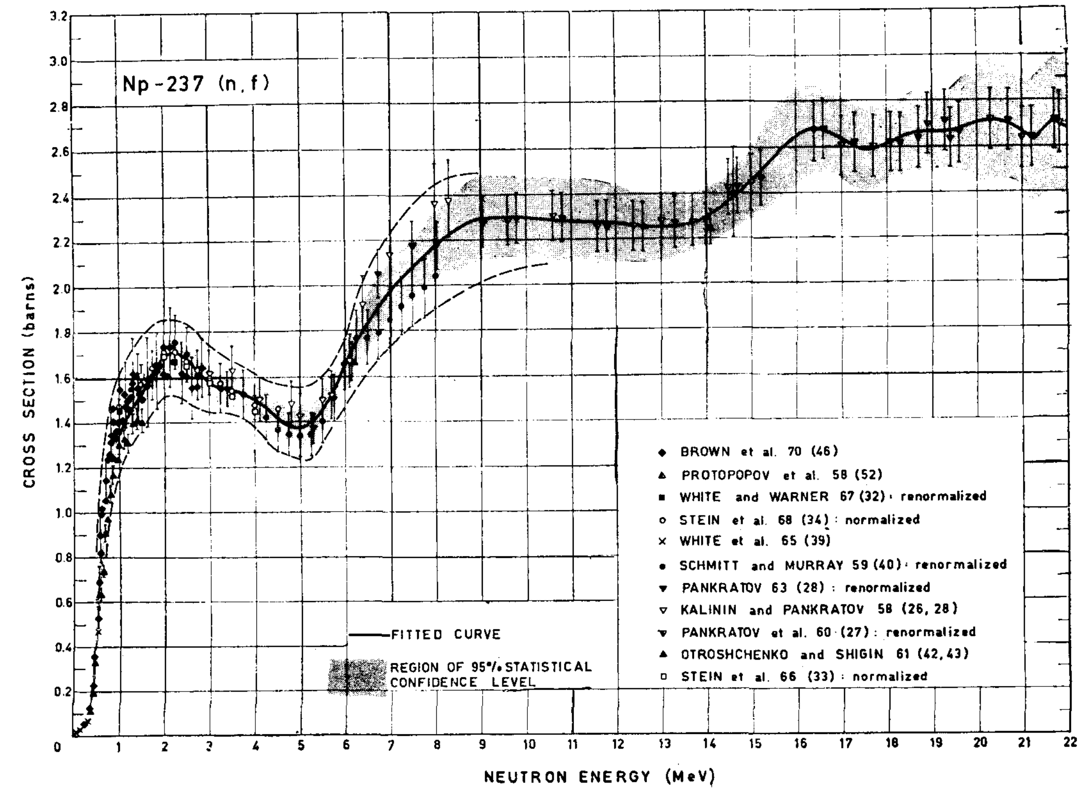

Fig. 3. Np-237 (n, f) excitation curve

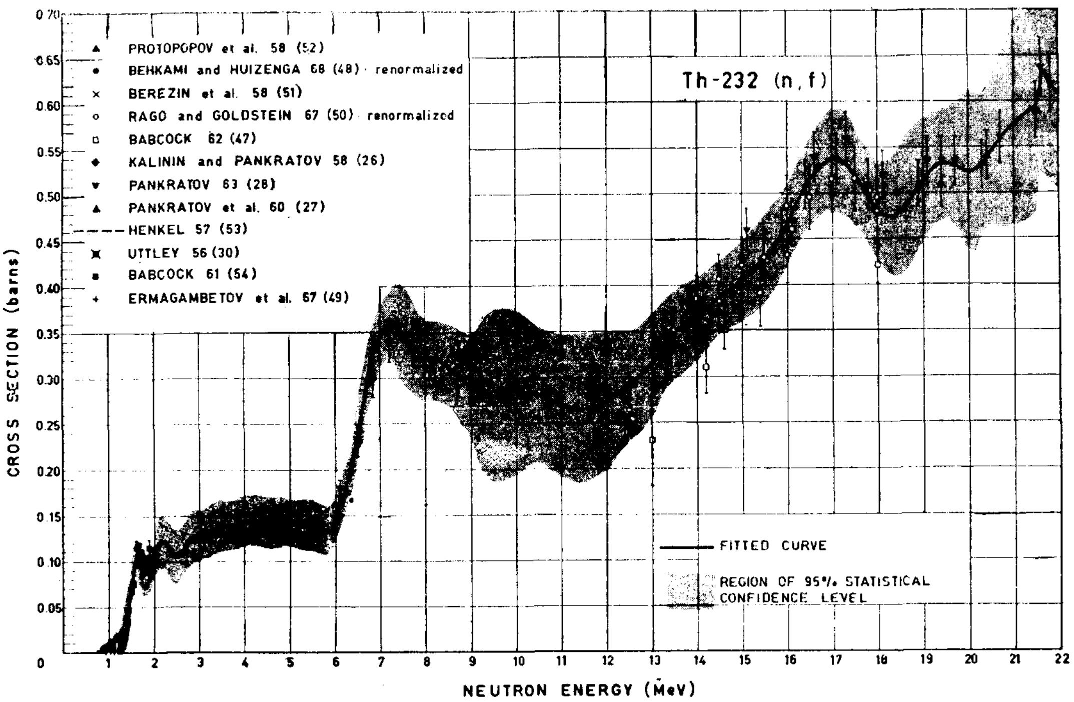

Fig. 4. Th-232 (n, f) excitation curve

presence of a finer structure became apparent immediately beyond the crests of each of the cross-section plateaux. This behaviour is readily seen in the figures given here, and is typically exemplified by Henkel's Th-232 data (Ref. 53) around 2 MeV, shown on Fig. 4 as a dashed curve. Although the data tend to indicate similar behaviour of the cross-section in the plateau regions of U-238 and Np-237, no fine resolution data, as in the case of Thorium, is presently available to resolve a well defined structure.

In this analysis, mainly because of the lack of high accuracy and high energy resolution of the available data, no exact fitting of the fine structure has been attempted, with the exception of the Thorium first plateau region which is relatively well defined by Henkel's data. Unfortunately no other data, of comparable density and accuracy has been measured since then for the three considered cross-sections. In the Thorium case, close to one hundred points in the energy range between 1.15 MeV and 9.00 MeV at 0.10 MeV intervals read from the curve, were supplemented to the input data. A 5% overall error was assigned to the data with due account of the 3.5% uncertainty of the standard used. Although a 40 degree fit of the data over a limited energy range provides an excellent point-wise agreement with the experimental data, the corresponding uncertainty at such high degree fits becomes considerably worse, and can only be reduced if much more limited energy ranges are analyzed with lower degree polynomials. In the final analysis, the Thorium fission cross-section was fitted in two separate runs as indicated in Table 1. Thus, under the present circumstances, the fitting could provide only an overall, or rough, structural detail of the cross-section dependence.

It is evident that in any application of these threshold reactions, such as in differential neutron flux measurements, an accurate knowledge of such fine structure would play an essential role in the improvement of the accur-

Table 2—1. Fitted fission cross-sections for U-238

Energy(MEV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
0.10	0.0	0.0	4.80	0.5051	0.0422
0.20	0.0	0.0	4.90	0.5046	0.0431
0.30	0.0	0.0	5.00	0.5058	0.0443
0.40	0.0	0.0	5.10	0.5092	0.0456
0.50	0.0	0.0	5.20	0.5148	0.0471
0.60	0.0012	0.0002	5.30	0.5229	0.0489
0.70	0.0012	0.0002	5.40	0.5336	0.0511
0.80	0.0036	0.0007	5.50	0.5468	0.0535
0.90	0.0092	0.0018	5.60	0.5624	0.0563
1.00	0.0192	0.0038	5.70	0.5803	0.0594
1.10	0.0242	0.0049	5.80	0.6002	0.0625
1.20	0.0358	0.0072	5.90	0.6219	0.0657
1.30	0.0745	0.0149	6.00	0.6449	0.0688
1.40	0.1493	0.0298	6.10	0.6690	0.0716
1.50	0.2501	0.0498	6.20	0.6937	0.0741
1.60	0.3473	0.0550	6.30	0.7187	0.0762
1.70	0.4120	0.0517	6.40	0.7436	0.0778
1.80	0.4647	0.0497	6.50	0.7680	0.0790
1.90	0.5041	0.0481	6.60	0.7917	0.0797
2.00	0.5306	0.0463	6.70	0.8143	0.0800
2.10	0.5455	0.0443	6.80	0.8356	0.0801
2.20	0.5508	0.0424	6.90	0.8554	0.0799
2.30	0.5488	0.0411	7.00	0.8735	0.0796
2.40	0.5419	0.0407	7.10	0.8899	0.0793
2.50	0.5322	0.0413	7.20	0.9044	0.0791
2.60	0.5216	0.0424	7.30	0.9171	0.0790
2.70	0.5117	0.0435	7.40	0.9280	0.0789
2.80	0.5035	0.0441	7.50	0.9371	0.0790
2.90	0.4976	0.0441	7.60	0.9447	0.0791
3.00	0.4943	0.0437	7.70	0.9507	0.0793
3.10	0.4936	0.0428	7.80	0.9553	0.0794
3.20	0.4951	0.0419	7.90	0.9587	0.0794
3.30	0.4984	0.0412	8.00	0.9611	0.0793
3.40	0.5029	0.0408	8.10	0.9627	0.0792
3.50	0.5080	0.0408	8.20	0.9635	0.0790
3.60	0.5131	0.0410	8.30	0.9638	0.0788
3.70	0.5177	0.0414	8.40	0.9637	0.0786
3.80	0.5214	0.0416	8.50	0.9633	0.0785
3.90	0.5239	0.0417	8.60	0.9628	0.0786
4.00	0.5250	0.0416	8.70	0.9622	0.0789
4.10	0.5247	0.0413	8.80	0.9616	0.0793
4.20	0.5231	0.0410	8.90	0.9611	0.0800
4.30	0.5205	0.0406	9.00	0.9606	0.0809
4.40	0.5172	0.0405	9.10	0.9603	0.0818
4.50	0.5136	0.0405	9.20	0.9601	0.0828
4.60	0.5101	0.0408	9.30	0.9601	0.0837
4.70	0.5071	0.0414	9.40	0.9601	0.0845

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
9.50	0.9602	0.0852	14.30	1.1533	0.0414
9.60	0.9603	0.0856	14.40	1.1653	0.0417
9.70	0.9604	0.0859	14.50	1.1775	0.0422
9.80	0.9605	0.0859	14.60	1.1895	0.0428
9.90	0.9605	0.0858	14.70	1.2015	0.0434
10.00	0.9604	0.0855	14.80	1.2132	0.0442
10.10	0.9602	0.0852	14.90	1.2246	0.0450
10.20	0.9599	0.0848	15.00	1.2357	0.0459
10.30	0.9594	0.0845	15.10	1.2462	0.0468
10.40	0.9588	0.0844	15.20	1.2562	0.0478
10.50	0.9582	0.0844	15.30	1.2655	0.0488
10.60	0.9574	0.0845	15.40	1.2740	0.0498
10.70	0.9566	0.0847	15.50	1.2816	0.0509
10.80	0.9558	0.0850	15.60	1.2884	0.0518
10.90	0.9550	0.0854	15.70	1.2942	0.0526
11.00	0.9542	0.0856	15.80	1.2990	0.0533
11.10	0.9537	0.0858	15.90	1.3027	0.0539
11.20	0.9533	0.0857	16.00	1.3055	0.0543
11.30	0.9531	0.0854	16.10	1.3074	0.0545
11.40	0.9532	0.0848	16.20	1.3083	0.0547
11.50	0.9537	0.0839	16.30	1.3085	0.0549
11.60	0.9546	0.0826	16.40	1.3080	0.0552
11.70	0.9559	0.0812	16.50	1.3069	0.0556
11.80	0.9576	0.0795	16.60	1.3054	0.0562
11.90	0.9599	0.0776	16.70	1.3038	0.0570
12.00	0.9626	0.0756	16.80	1.3020	0.0581
12.10	0.9658	0.0736	16.90	1.3004	0.0593
12.20	0.9696	0.0716	17.00	1.2992	0.0606
12.30	0.9740	0.0697	17.10	1.2984	0.0619
12.40	0.9788	0.0678	17.20	1.2982	0.0631
12.50	0.9842	0.0661	17.30	1.2988	0.0641
12.60	0.9901	0.0644	17.40	1.3003	0.0650
12.70	0.9965	0.0628	17.50	1.3027	0.0657
12.80	1.0033	0.0612	17.60	1.3060	0.0662
12.90	1.0107	0.0596	17.70	1.3103	0.0666
13.00	1.0185	0.0580	17.80	1.3155	0.0669
13.10	1.0267	0.0562	17.90	1.3214	0.0673
13.20	1.0354	0.0544	18.00	1.3280	0.0677
13.30	1.0444	0.0526	18.10	1.3350	0.0681
13.40	1.0539	0.0507	18.20	1.3423	0.0684
13.50	1.0637	0.0488	18.30	1.3497	0.0686
13.60	1.0739	0.0470	18.40	1.3570	0.0685
13.70	1.0844	0.0453	18.50	1.3639	0.0682
13.80	1.0952	0.0439	18.60	1.3703	0.0677
13.90	1.1064	0.0428	18.70	1.3761	0.0671
14.00	1.1178	0.0420	18.80	1.3812	0.0667
14.10	1.1294	0.0415	18.90	1.3855	0.0670
14.20	1.1413	0.0413	19.00	1.3890	0.0682

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta igma (Barns)
19.10	1.3920	0.0708	19.60	1.4052	0.0958
19.20	1.3945	0.0747	19.70	1.4095	0.0996
19.30	1.3968	0.0797	19.80	1.4150	0.1020
19.40	1.3991	0.0853	19.90	1.4217	0.1027
19.50	1.4018	0.0909	20.00	1.4298	0.1020

Table 2—2. Fitted fission cross-sections for Np-237.

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
0.10	0.0246	0.0046	3.90	1.5154	0.0731
0.20	0.0383	0.0055	4.00	1.5033	0.0735
0.30	0.0816	0.0097	4.10	1.4886	0.0744
0.40	0.2203	0.0222	4.20	1.4717	0.0760
0.50	0.4499	0.0428	4.30	1.4534	0.0783
0.60	0.7341	0.0633	4.40	1.4346	0.0810
0.70	0.9707	0.0762	4.50	1.4165	0.0840
0.80	1.1542	0.0583	4.60	1.4001	0.0868
0.90	1.2789	0.0557	4.70	1.3866	0.0893
1.00	1.3598	0.0545	4.80	1.3769	0.0915
1.10	1.4099	0.0560	4.90	1.3719	0.0934
1.20	1.4429	0.0587	5.00	1.3722	0.0952
1.30	1.4696	0.0606	5.10	1.3782	0.0971
1.40	1.4972	0.0611	5.20	1.3900	0.0990
1.50	1.5289	0.0610	5.30	1.4075	0.1011
1.60	1.5647	0.0615	5.40	1.4304	0.1033
1.70	1.6025	0.0630	5.50	1.4580	0.1055
1.80	1.6389	0.0646	5.60	1.4897	0.1077
1.90	1.6706	0.0655	5.70	1.5247	0.1098
2.00	1.6948	0.0650	5.80	1.5621	0.1119
2.10	1.7096	0.0633	5.90	1.6011	0.1139
2.20	1.7145	0.0614	6.00	1.6408	0.1161
2.30	1.7100	0.0602	6.10	1.6805	0.1184
2.40	1.6974	0.0602	6.20	1.7194	0.1209
2.50	1.6790	0.0612	6.30	1.7571	0.1236
2.60	1.6570	0.0626	6.40	1.7932	0.1264
2.70	1.6338	0.0636	6.50	1.8273	0.1291
2.80	1.6115	0.0638	6.60	1.8593	0.1316
2.90	1.5915	0.0635	6.70	1.8893	0.1336
3.00	1.5749	0.0631	6.80	1.9173	0.1350
3.10	1.5620	0.0630	6.90	1.9435	0.1358
3.20	1.5528	0.0638	7.00	1.9682	0.1359
3.30	1.5466	0.0655	7.10	1.9915	0.1356
3.40	1.5425	0.0676	7.20	2.0137	0.0350
3.50	1.5393	0.0697	7.30	2.0351	0.1344
3.60	1.5359	0.0713	7.40	2.0560	0.1341
3.70	1.5313	0.0724	7.50	2.0765	0.1345
3.80	1.5246	0.0728	7.60	2.0966	0.1358

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Enargy(MeV)	Sigma(Barns)	Delta Sigma (Brans)
7.70	2.1165	0.1382	12.50	2.2572	0.1599
7.80	2.1361	0.1418	12.60	2.2559	0.1591
7.90	2.1553	0.1465	12.70	2.2550	0.1592
8.00	2.1741	0.1521	12.80	2.2546	0.1598
8.10	2.1923	0.1584	12.90	2.2547	0.1606
8.20	2.2096	0.1652	13.00	2.2553	0.1610
8.30	2.2259	0.1720	13.10	2.2565	0.1608
8.40	2.2410	0.1785	13.20	2.2582	0.1596
8.50	2.2547	0.1845	13.30	2.2604	0.1574
8.60	2.2668	0.1896	13.40	2.2632	0.1543
8.70	2.2773	0.1936	13.50	2.2666	0.1505
8.80	2.2861	0.1964	13.60	2.2706	0.1465
8.90	2.2931	0.1978	13.70	2.2754	0.1426
9.00	2.2983	0.1978	13.80	2.2809	0.1394
9.10	2.3020	0.1965	13.90	2.2874	0.1370
9.20	2.3042	0.1941	14.00	2.2949	0.1355
9.30	2.3050	0.1909	14.10	2.3037	0.1347
9.40	2.3047	0.1874	14.20	2.3137	0.1343
9.50	2.3036	0.1839	14.30	2.3253	0.1340
9.60	2.3017	0.1809	14.40	2.3384	0.1338
9.70	2.2995	0.1788	14.50	2.3532	0.1340
9.80	2.2969	0.1779	14.60	2.3698	0.1352
9.90	2.2944	0.1782	14.70	2.3880	0.1383
10.00	2.2919	0.1796	14.80	2.4078	0.1442
10.10	2.2897	0.1818	14.90	2.4292	0.1535
10.20	2.2879	0.1844	15.00	2.4518	0.1661
10.30	2.2864	0.1869	15.10	2.4754	0.1814
10.40	2.2853	0.1889	15.20	2.4997	0.1984
10.50	2.2846	0.1903	15.30	2.5241	0.2157
10.60	2.2843	0.1908	15.40	2.5483	0.2321
10.70	2.2841	0.1905	15.50	2.5717	0.2462
10.80	2.2841	0.1895	15.60	2.5938	0.2570
10.90	2.2841	0.1881	15.70	2.6142	0.2639
11.00	2.2841	0.1864	15.80	2.6323	0.2663
11.10	2.2839	0.1848	15.90	2.6477	0.2641
11.20	2.2835	0.1835	16.00	2.6601	0.2577
11.30	2.2828	0.1825	16.10	2.6693	0.2476
11.40	2.2817	0.1818	16.20	2.6750	0.2349
11.50	2.2802	0.1813	16.30	2.6774	0.2206
11.60	2.2785	0.1807	16.40	2.6766	0.2063
11.70	2.2763	0.1798	16.50	2.6728	0.1935
11.80	2.2740	0.1784	16.60	2.6664	0.1832
11.90	2.2714	0.1764	16.70	2.6579	0.1763
12.00	2.2687	0.1737	16.80	2.6480	0.1727
12.10	2.2661	0.1706	16.90	2.6372	0.1720
12.20	2.2635	0.1673	17.00	2.6263	0.1733
12.30	2.2611	0.1642	17.10	2.6159	0.1757
12.40	2.2590	0.1616	17.20	2.6066	0.1784

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
17.30	2.5989	0.1811	18.70	2.6627	0.1845
17.40	2.5934	0.1836	18.80	2.6659	0.1859
17.50	2.5902	0.1855	18.90	2.6678	0.1840
17.60	2.5895	0.1867	19.00	2.6687	0.1789
17.70	2.5914	0.1870	19.10	2.6691	0.1719
17.80	2.5955	0.1860	19.20	2.6693	0.1661
17.90	2.6016	0.1839	19.30	2.6699	0.1653
18.00	2.6093	0.1807	19.40	2.6712	0.1723
18.10	2.6180	0.1772	19.50	2.6735	0.1873
18.20	2.6271	0.1743	19.60	2.6769	0.2081
18.30	2.6361	0.1730	19.70	2.6815	0.2309
18.40	2.6445	0.1739	19.80	2.6870	0.2527
18.50	2.6520	0.1770	19.90	2.6931	0.2711
18.60	2.6580	0.1810	20.00	2.6993	0.2843

Table 2-3. Fitted fission cross-sections for Th-232

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barna)	Delta Sigma (Brans)
0.10	0.0	0.0	3.00	0.1284	0.0274
0.20	0.0	0.0	3.10	0.1287	0.0267
0.30	0.0	0.0	3.20	0.1312	0.0258
0.40	0.0	0.0	3.30	0.1352	0.0253
0.50	0.0	0.0	3.40	0.1386	0.0249
0.60	0.0	0.0	3.50	0.1400	0.0249
0.70	0.0	0.0	3.60	0.1395	0.0254
0.80	0.0	0.0	3.70	0.1387	0.0261
0.90	0.0	0.0	3.80	0.1391	0.0263
1.00	0.0014	0.0003	3.90	0.1411	0.0267
1.10	0.0030	0.0006	4.00	0.1437	0.0270
1.20	0.0061	0.0012	4.10	0.1455	0.0264
1.30	0.0129	0.0026	4.20	0.1454	0.0256
1.40	0.0406	0.0081	4.30	0.1441	0.0260
1.50	0.0825	0.0165	4.40	0.1428	0.0271
1.60	0.1046	0.0213	4.50	0,1426	0.0276
1.70	0.0982	0.0215	4.60	0.1439	0.0272
1.80	0.0861	0.0228	4.70	0.1456	0.0269
1.90	0.0895	0.0235	4.80	0.1463	0.0264
2.00	0.1068	0.0264	4.90	0.1451	0.0258
2.10	0.1222	0.0303	5.00	0.1424	0.0261
2.20	0.1244	0.0308	5.10	0.1397	0.0265
2.30	0.1154	0.0302	5.20	0.1383	0.0256
2.40	0.1058	0.0305	5.30	0.1385	0.0245
2.50	0.1038	0.0299	5.40	0.1392	0.0256
2.60	0.1101	0.0293	5.50	0.1387	0.0275
2.70	0.1196	0.0296	5.60	0.1365	0.0280
2.80	0.1265	0.0292	5.70	0.1335	0.0276
2.90	0.1288	0.0281	5.80	0.1326	0.0273

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
5.90	0.1365	0.0261	10.70	0.2781	0.0768
6.00	0.1460	0.0241	10.80	0.2758	0.0794
6.10	0.1599	0.0240	10.90	0.2735	0.0833
6.20	0.1760	0.0260	11.00	0.2713	0.0878
6.30	0.1931	0.0281	11.10	0.2694	0.0922
6.40	0.2125	0.0286	11.20	0.2678	0.0960
6.50	0.2364	0.0281	11.30	0.2668	0.0987
6.60	0.2649	0.0285	11.40	0.2663	0.0998
6.70	0.2941	0.0276	11.50	0.2665	0.0993
6.80	0.3181	0.0232	11.60	0.2672	0.0973
6.90	0.3338	0.0259	11.70	0.2685	0.0937
7.00	0.3439	0.0322	11.80	0.2703	0.0890
7.10	0.3532	0.0320	11.90	0.2725	0.0836
7.20	0.3609	0.0321	12.00	0.2752	0.0780
7.30	0.3604	0.0341	12.10	0.2782	0.0726
7.40	0.3543	0.0565	12.20	0.2815	0.0678
7.50	0.3462	0.0551	12.30	0.2849	0.0640
7.60	0.3375	0.0499	12.40	0.2885	0.0611
7.70	0.3300	0.0453	12.50	0.2923	0.0591
7.80	0.3246	0.0438	12.60	0.2961	0.0577
7.90	0.3215	0.0440	12.70	0.3001	0.0566
8.00	0.3201	0.0441	12.80	0.3041	0.0555
8.10	0.3198	0.0438	12.90	0.3083	0.0543
8.20	0.3197	0.0437	13.00	0.3126	0.0530
8.30	0.3192	0.0443	13.10	0.3171	0.0517
8.40	0.3177	0.0451	13.20	0.3218	0.0506
8.50	0.3151	0.0452	13.30	0.3267	0.0497
8.60	0.3114	0.0445	13.40	0.3317	0.0491
8.70	0.3068	0.0437	13.50	0.3369	0.0488
8.80	0.3016	0.0445	13.60	0.3422	0.0486
8.90	0.2964	0.0485	13.70	0.3476	0.0485
9.00	9.2914	0.0557	13.80	0.3530	0.0482
9.10	0.2870	0.0648	13.90	0.3584	0.0476
9.20	0.2835	0.0744	14.00	0.3637	0.0467
9.30	0.2809	0.0830	14.10	0.3688	0.0454
9.40	0.2794	0.0900	14.20	0.3737	0.0440
9.50	0.2789	0.0949	14.30	0.3783	0.0427
9.60	0.2791	0.0977	14.40	0.3826	0.0416
9.70	0.2799	0.0985	14.50	0.3867	0.0410
9.80	0.2810	0.0977	14.60	0.3904	0.0411
9.90	0.2823	0.0957	14.70	0.3939	0.0418
10.00	0.2834	0.0927	14.80	0.3973	0.0430
10.10	0.2841	0.0892	14.90	0.4006	0.0446
10.20	0.2844	0.0854	15.00	0.4041	0.0462
10.30	0.2842	0.0817	15.10	0.4077	0.0478
10.40	0.2834	0.0786	15.20	0.4116	0.0491
10.50	0.2821	0.0765	15.30	0.4160	0.0499
10.60	0.2803	0.0758	15.40	0.4211	0.0504

Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)	Energy(MeV)	Sigma(Barns)	Delta Sigma (Barns)
15.50	0.4268	0.0504	17.80	0.4957	0.0503
15.60	0.4333	0.0500	17.90	0.4886	0.0515
15.70	0.4406	0.0493	18.00	0.4826	0.0542
15.80	0.4487	0.0483	18.10	0.4782	0.0578
15.90	0.4575	0.0471	18.20	0.4755	0.0620
16.00	0.4669	0.0460	18.30	0.4748	0.0661
16.10	0.4766	0.0451	18.40	0.4762	0.0698
16.20	0.4865	0.0446	18.50	0.4796	0.0726
16.30	0.4964	0.0446	18.60	0.4846	0.0743
16.40	0.5059	0.0454	18.70	0.4911	0.0746
16.50	0.5146	0.0468	18.80	0.4985	0.0736
16.60	0.5224	0.0488	18.90	0.5062	0.0712
16.70	0.5289	0.0511	19.00	0.5136	0.0676
16.80	0.5338	0.0535	19.10	0.5204	0.0635
16.90	0.5370	0.0556	19.20	0.5258	0.0596
17.00	0.5384	0.0571	19.30	0.5296	0.0574
17.10	0.5378	0.0580	19.40	0.5317	0.0581
17.20	0.5354	0.0579	19.50	0.5320	0.0621
17.30	0.5312	0.0571	19.60	0.5308	0.0687
17.40	0.5256	0.0555	19.70	0.5286	0.0763
17.50	0.5188	0.0536	19.80	0.5260	0.0832
17.60	0.5113	0.0517	19.90	0.5239	0.0880
17.70	0.5034	0.0504	20.00	0.5228	0.0896

acy of such measurements. For the purpose of most threshold activation detectors presently used, however, the detailed shapes of the fine structure of these cross sections are not known well enough.

5. Calculation of the fission spectrum averaged fission cross section

An approximate calculation of the fission spectrum weighted average fission cross section values of U-238, Np-237 and Th-232 was performed with the point-wise data obtained from the fitting procedure described above. In addition, an estimate of the uncertainty of the calculated average cross-sections was made on the basis of the calculated uncertainties of the fitted data points.

Considering equal energy integraton intervals $\triangle E$ of 0.1 MeV, and using a simple histogram integration method, the average weighted cross-section was calculated from the following expression for the three considered cross-sections between 0 and 20 MeV.

$$\bar{\sigma}_f = \frac{\Sigma \sigma_f(E_i)\phi(E_i)}{\Sigma \phi(E_i)}$$

Where $\sigma_f(E_i)$ are the point-wise fitted fission cross-sections at energies E_i, and $\phi(E_i)$ are the point-wise values of the watt fission spectrum as given by Frye, et al. (Ref. 67):

$$\phi(E) \propto \exp(-E/0.965) * \sinh\sqrt{2.29E}$$

In combining the components of systematic effects to give an overall measure of the resultant uncertainty, two methods can be adopted (see Ref. 66). One combines the errors by arithmetic addition, the other sums them in quadrature. While the linear combination method is apt to overestimate the overall uncertainty, the quadrature method, which is similar to the method used in the treatment of statistical error propagation, usually tends to underestimate the overall uncertainty.

Table 3. Comparison of fission spectrum averaged cross sections (σ_f)

Reaction	Authors (Reference given in parenthesis)	σ_f (mb)	Remarks
U-238 (n, f)	Present work	285. ± 27.	Calc. Frye-Spectrum with fitted cross-sections (Integrated between 0 and 20 MeV).
	Bresesti et al. 63 (56)	312.	Calculation
	Durham et al. 62 (55)	310.	Assumed value
	Zijp 63 (57)	301.	Calculation
	Grundl 63 (58)	313.	Assumed value
	Grundl 63 (58)	300.	Calc. Maxwell-Spectr.
	Grundl 63 (58)	309.	Calc. Watt-Spectrum
	Richmond 57 (59)	304. ± 7.	Measured
		312. ± 5.	Adjusted to $\bar{\nu}$=2.42
	Leachman and Schmitt 57 (60)	310. ± 4.0	Measured
	Nikolaev et al. 58 (61)	310. ± 10.0	Measured
	Fabry and De Coster 68 (62)	353. ± 30.0	Measured
	McElroy 69 (64)	335.	Calc. SAND-II
	Bresti et al. 70 (3)	269.0	Calc. Watt-Spectrum
	Breseti et al. 70 (3)	294.0	Calc. Frye-Spectrum
	Bresesti et al. 70 (3)	283.0	Calc. Maxwell-Spec.
	Bresesti et al. 70 (3)	308.0 ± 15.0	Renormalization of experimental data. Calc. Watt-Spec.
	Crundl 68 (63, 4)	325. ± 19.	Measured
	Fabry et al. 70 (4)	374. ± 30.	Measured
Np-237(n. f)	Present work	*1289. ± 87.	Calc. Frye-Spectrum with fitted cross sections (integrated between 0 and 20 MeV)
	Bresesti et al. 63 (56)	1174.	Calculation
	Zijp 63(57)	1323.	Calculation
	Grundl 63 (58)	1355.	U-238 (n, f)=313mb
	Crundl 63 (58)	1370.	Calc. Maxwell-Spec.
	Crundl 63 (58)	1391.	Calc. Watt-Spec.
	Crundl 68 (63, 4)	1365. ± 95.	Measured
	McElroy 69 (64)	1368.	Calc. SAND-II
	Hinkelmann 70 (65)	*1570.	Calc. Frye-Spec., with fitted cross sections (integrated between 0.8 and 10. MeV)
Th-232 (n, f)	Present work	70.2 ± 13.5	Calc. Frye-Spec. with fitted cross sections (integrated between 0 and 200 MeV)
	Bresesti et al. 63 (56)	71.9	Calculation
	Fabry et al. 70 (4)	87.5 ± 3.5	Measured

* Results of integrating the data obtained in this work between 0.8 and 10 MeV yields a flux weighted average cross section of 1536.0 mb.

Both of these methods were used to estimate the overall uncertainty of the weighted average cross-sectins $\bar{\sigma}_f$:

1) $\overline{\Delta\sigma_f}$ calculated on the basis of the quadrature summation method are 0.9%, 0.7% and 3.6% for U-238, Np-237 and Th-232, respectively.

2) $\overline{\Delta\sigma_f}$ calculated on the basis of the arithmetic summation method are 9.4%, 6.7% and 19% for U-238, Np-237 and Th-232, respectively.

The results obtained in this evaluation of the weighted average fission cross-sections and their uncertainties, are given together with experimental and calculated results of other authors

Table 4. Percent response of threshold detectors in Frye spectrum

Energy Range (MeV)	U-238 (n, f)	Np-237 (n, f)	Th-232 (n, f)
0—1	0.43	17.20	(0.10)
1—2	26.50	35.00	24.60
2—3	33.60	23.40	30.50
3—4	17.92	12.00	19.60
4—5	9.44	5.79	10.70
5—6	5.07	2.97	5.12
6—7	3.38	1.78	4.31
7—8	1.95	0.96	2.92
8—9	0.93	0.48	1.23
9—10	0.43	0.24	0.50
10—15	0.34	0.18	0.40
15—20	0.01	0	0.02

in Table 3. The uncertanities quoted in this table, and the ones which are considered to be the more realistic are those calculated by the method of arithmetic summation.

Supplementary information which may be of interest in comparing the response of the three considered threshold fission detectors is given in Table 4. This tabulated information lists the percent response of U-238, Np-237 and Th-232 fission detectors in a Frye-type spectrum for specific energy intervals between 0 and 20 MeV.

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