International Atomic Energy Agency

INDC(NDS)-36/G

Draft.

INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

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

H.I. Bak and A. Lorenz

IAEA Nuclear Data Section

Vienna, Austria

August 1971

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

REVIEW OF THE CURRENT STATUS OF THE U-238, NP-237 AND TH-232 FISSION CROSS SECTIONS

H.I. Bak * and A. Lorenz

IAEA Nuclear Data Section
Vienna, Austria

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.

* Presently at Seoul University, Seoul, Korea.

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 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 a 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 percent 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.

II. 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; those 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% and 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 normalised 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 measurement 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 been 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.
Original 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%.

III. 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_i, is considered to be inversely proportional to either $(\Delta\sigma)^2$ (absolute weight) or $(\Delta\sigma/\sigma)^2$ (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 $\left(\frac{\Delta\sigma}{\sigma}\right)^2$) 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 program. 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. $\Delta\sigma$), 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, such as the threshold regions of the U-238 and Np-237 cross-section, were fitted separately using the absolute error values in order to reduce the resultant uncertainties of the fitted points and eliminate undesirable oscillations of the fitted function.

TABLE 1. Fitting Parameters

REACTION	E_n (MeV) E_{min}	E_{max}	n	k	f	REMARKS
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 ≤ 1.5 MeV
				20	2.96	Data were weighted according to the inverse square of the relative error for energy range ≥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 ≤0.7 MeV
				26	3.17	Data were weighted according to the inverse square of the relative error for energy range ≥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 (uncertainties were used (in both fits
	7.0	22.0		19	3.015	

Parameter descriptions: n = total number of input data points;
k = chosen degree of fit;
f = weighting factor to convert from point-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.

IV. 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 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 accuracy 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.

V. 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 integration intervals ΔE 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.

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

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.

Both of these methods were used to estimate the overall uncertainty of the weighted average cross-sections $\overline{\sigma_f}$:

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 in Table 3. The uncertainties 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 KeV.

*
* *

Acknowledgement

The authors want to thank Dr. J.J. Schmidt and Dr. T.A. Byer for their support and helpful advice.

REFERENCES

1. W.L. Zijp, "Review of Activation Methods for the Determination of Fast Neutron Spectra", RCN-37, Reactor Centrum Nederland, Petten, Netherlands (1965)

2. C.R. Lubitz and L. Stewart, "Remarks on the Neutron-Induced Fission Spectrum", EANDC(US)-139"L" (1970)

3. A.M. Bresesti, M. Bresesti, A. Rota, R.A. Rydin, and L. Lesca, Nucl. Sci. Eng., 40, 331 (1970)

4. A. Fabry, M. De Coster, G. Minsart, J.C. Schepers, and P. Vandeplas, "IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970", CN-26/39 (1970)

5. G. Ben-David, Techn. Report "Nuclear Standards for Neutron Measurements", IAEA-107, 57, IAEA, Vienna (1968)

6. Technical Reports Series No. 107, "Neutron Fluence Measurements", IAEA, Vienna (1970)

7. H. Liskien and A. Paulsen, "Compilation of Cross Section for Some Neutron Induced Threshold Reactions", EURATOM, Central Bureau for Nuclear Measurements, Geel, Belgium (Nov. 1961)

8. H. Liskien and A. Paulsen, "Compilation of Cross Sections for Some Neutron Induced Threshold Reactions", EUR 119.e Vol. 1 (May 1965) and Vol. 2 (April 1967), Central Bureau for Nuclear Measurements, Geel, Belgium

9. J. Spaepen and H. Liskien, Tech. Report "Nuclear Standards for Neutron Measurements", IAEA-107, 259, IAEA, Vienna (1968)

10. K. Parker, "Neutron Cross Sections of U-235 and U-238 in the Energy Range 1 KeV to 15 MeV, Part II", AWRE 0-82/63, AWRE Aldermaston, England (1963)

11. I. Langner, J.J. Schmidt, and D. Woll, "Tables of Evaluated Neutron Cross Sections for Fast Reactor Materials", KFK-750 (1968)

12. W.G. Davey, Nucl. Sci. Eng., 26, 149 (1966)

13. W.G. Davey, Nucl. Sci. Eng., 32, 35 (1968)

14. Y. Kanda and R. Nakasima, " Review of Some Fast Neutron Cross Section Data", Neutron Cross Sections and Technology, Proceedings of a Conference, Washington, D.C., Vol. 1, 193 (March 1968)

15. W. Hart, "Revised Fission Cross Section Evaluations for the Energy Range 1 KeV to 15 MeV", AHSB(S)R 169 (1969)

16. H. Alter and C.L. Dunford, "An Evaluation of Uranium-235 Neutron Cross Section Data for Energies above 15 KeV", AI-AEC-MEMO-12916, Atomics International, North American Rockwell (1970)

17. A. Horsley and J.B. Parker, Supplement to the Proceedings of a Conference, Paris, "Nuclear Data for Reactors", INDC-156, CN-23/24, IAEA, Vienna (1967)

18. J.R. Smith and R.A. Grimesey, "An Evaluation and Compilation of Neptunium-237 Cross Section Data for the ENDF/B File", IN-1182 (May 1969)

19. A Least-Squares Orthogonal Polynomial Fitting Programme from CERN 7090 Programme Library (1970)

20. Derek J. Hudson, "Statistics Lectures II", CERN 64-18, Data Handling Division, CERN-Geneva (1964)

21. RENDA, Compilation of EANDC Requests for Neutron Data Measurements, EANDC 85"U" (April 1970)

22. J.J. Schmidt, Private communication (1969)

23. R.K. Smith, R.L. Henkel, and R.A. Nobles, Bull. Am. Phys. Soc., 2, 196 (1957)

24. G. Hansen, S. McGuire, and R.K. Smith, "Reports to the AEC Neutron Cross Section Advisory Group Meeting at Brookhaven, New York, April 13-14, 1967", WASH-1074, 75 (1967)

25. R.K. Smith, "Correction to Data of Smith, et al., Bull. Am. Phys. Soc., 2, 196 (1957)", Private communication to BNL (1968)

26. S.P. Kalinin and V.M. Pankratov, Proc. 2nd Intern. Conf. Peaceful Uses At. Energy, 16, 136 (1958)

27. V.M. Pankratov, N.A. Vlasov, and B.V. Rybakov, Atomnaya Energiya, 9, 399 (1960). Transl. in Soviet Atomic Energy, 9, 939 (1961) and J. Nucl. Energy, 16, 494 (1962)

28. V.M. Pankratov, Atomnaya Energiya, 14, 177 (1963). Transl. in Soviet Atomic Energy, 14, 167 (1963) and Journal of Nuclear Energy, Part A/B (Reactor Science and Technology), 18, 215 (1964)

29. A. Moat, Private communication to BNL (1958)

30. C.A. Uttley and J.A. Phillips, AERE NP/R 1996 (1956)

31. W. Nyer, LA-719 (1948)

32. P.H. White and G.P. Warner, J. Nucl. Energy, 21, 671 (1967)

33. W.E. Stein, R.K. Smith, and J.A. Grundl, "Relative Fission Cross Sections of U-238, Np-237, and U-235", CONF-660303, 623, Physical Society Conference on Neutron Cross Section Technology, Washington, D.C. (March 1966)

34. W.E. Stein, R.K. Smith, and H.L. Smith, "Relative Fission Cross Sections of U-236, U-238, Np-237, and U-235", Neutron Cross Sections and Technology, Proceedings of a Conference, Washington, D.C., Vol. 1, 627 (March 1968)

35. R.W. Lamphere, Phys. Rev., 104, 1654 (1956)

36. B. Adams, R. Batchelor, and T.S. Green, Reactor Sci. Tech., 14, 85 (1961)

37. V. Emma, S. LoNigro, C. Milone, and R. Ricamo, Nucl. Phys. 63, 641 (1965)

38. N.N. Flerov, A.A. Berezin, and I.E. Chelnokov, Atomnaya Energiya, 5, 657 (1958). Transl. in J. Nucl. Energy, 11, 173 (1959)

39. P.H. White, J.G. Hodgkinson, and G.J. Wall, Proc. Symp. IAEA Salzburg, Austria, "Physics and Chemistry of Fission", Vol. I, 219 (1965)

40. H.W. Schmitt and R.B. Murray, Phys. Rev., 116, 1575 (1959)

41. E.D. Klema, Phys. Rev., 72, 88 (1947)

42. G.A. Otroshchenko and V.A. Shigin, Neitronnya Fizika USSR. 155, Ed. by P.A. Krupchitskii, Moscow (1961). Transl. in Soviet Progress in Neutron Physics, 155, Consultants Bureau, New York (1963)

43. B.M. Gokhberg, G.A. Otroshchenko, and V.A. Shigin, Dokl. Akad. Nauk. USSR, 128, 1157 (1959). Transl. in Soviet Phys. Doklady, 4, 1074 (1959)

44. H. Condé et al., Conf. Proc. IAEA Paris, "Nuclear Data for Reactors", Vol. I, 419 (1967)

45. W.K. Brown, D.R. Dixon and D.M. Drake, Nuclear Physics A 156, 609 (1970)

46. W.K. Brown, D.R. Dixon and D.M. Drake, LA-4372 (March 1970)

47. R.V. Babcock, "Neutron Cross Section Evaluation Group Newsletter No. 6", page 2, BNL-732, Brookhaven National Laboratory (1962)

48. A.N. Behkami and J.R. Huizenga, Nucl. Phys., A118, 65 (1968)

49. S.B. Ermagambetov, F.V. Kuznetsov, and G.N. Smirenkin, INDSWG 152E, "USSR State Committee on the Utilization of Atomic Energy", page 5 (1967)

50. P.F. Rago and N. Goldstein, Health Physics, 13, 654 (1967)

51. A.A. Berezin, G.A. Stoliarov, Iu.V. Nikol'skii, and I.E. Chelnokov, Atomnaya Energiya, 5, 659 (1958). Transl. in Soviet Atomic Energy, 5, 1604 (1958) and J. Nucl. Energy, 11, 175 (1959/60)

52. A.N. Protopopov, Iu.A. Selitskii, and S.M. Solov'ev, Atomnaya Energiya, 4, 190 (1958). Transl. in J. Nucl. Energy, 9, 157 (1959) and Soviet Atomic Energy, 4, 256 (1958)

53. R.L. Henkel, "Fast Neutron Cross Sections", LA-2122, Los Alamos Scientific Laboratory (1957)

54. R.V. Babcock, Private communication to BNL (Oct. 1961)

55. R.W. Durham, M.P. Navalkar, E. Ricci, "Threshold Reaction Interference in Neutron Activation Analysis", AECL-1434 (January 1962)

56. M. Bresesti, A.M. Del Turco, A. Ostidich, A. Rota and G. Segre, Proc. Symp. IAEA Harwell, "Neutron Dosimetry", Vol. I, 27 (1963)

57. W.L. Zijp, RCN-Int-63-069 (Petten, September 1963)

58. J.A. Grundl, "Study of Fission Neutron Spectra with High-Energy Activation Detectors", LAMS-2883 (May 1963)

59. R. Richmond, unpublished, results quoted by W.D. Allen and R.L. Henkel, Progress in Nuclear Energy, Series I, 2, 1-50, Pergamon Press (1957)

60. R.B. Leachman and H.W. Schmitt, J. Nucl. Energy, 4, 38 (1957)

61. M.N. Nikolaev, V.I. Golubev and I.I. Bondarenko, J. Expt. Theoret. Phys., 7, 517 (1958)

62. A. Fabry and M. De Coster, "Integral Test of Capture Cross Sections in the Energy Range 0.1 - 2 MeV", Neutron Cross Sections and Technology, Proceedings of a Conference, Washington, D.C., Vol. 2, 1263 (March 1968)

63. J.A. Grundl, Nucl. Sci. Eng. 31, 191 (1968)

64. W.N. McElroy, Nucl. Sci. Eng. 36, 109 (1969)

65. B. Hinkelmann, EANDC(E)128"U" (KFK 1186) (July 1970)

66. P.J. Campion, J.E. Burns and A. Williams, "A Code of Practice for the Statement of Accuracy", EANDC(UK)128AL (1970)

67. L. Cranberg, G. Frye, N. Nereson, and L. Rosen, Phys. Rev., 103, 662 (1956)

TABLE 2-1. FITTED FISSION CROSS-SECTIONS FOR U-238

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
0.10	0.0	0.0
0.20	0.0	0.0
0.30	0.0	0.0
0.40	0.0	0.0
0.50	0.0	0.0
0.60	0.0012	0.0002
0.70	0.0012	0.0002
0.80	0.0036	0.0007
0.90	0.0092	0.0018
1.00	0.0192	0.0038
1.10	0.0242	0.0049
1.20	0.0358	0.0072
1.30	0.0745	0.0149
1.40	0.1493	0.0298
1.50	0.2501	0.0498
1.60	0.3473	0.0550
1.70	0.4120	0.0517
1.80	0.4647	0.0497
1.90	0.5041	0.0481
2.00	0.5306	0.0463
2.10	0.5455	0.0443
2.20	0.5508	0.0424
2.30	0.5488	0.0411
2.40	0.5419	0.0407
2.50	0.5322	0.0413
2.60	0.5216	0.0424
2.70	0.5117	0.0435
2.80	0.5035	0.0441
2.90	0.4976	0.0441
3.00	0.4943	0.0437
3.10	0.4936	0.0428
3.20	0.4951	0.0419
3.30	0.4984	0.0412
3.40	0.5029	0.0408
3.50	0.5080	0.0408
3.60	0.5131	0.0410
3.70	0.5177	0.0414
3.80	0.5214	0.0416
3.90	0.5239	0.0417
4.00	0.5250	0.0416
4.10	0.5247	0.0413
4.20	0.5231	0.0410
4.30	0.5205	0.0406
4.40	0.5172	0.0405
4.50	0.5136	0.0405
4.60	0.5101	0.0408
4.70	0.5071	0.0414
4.80	0.5051	0.0422
4.90	0.5046	0.0431
5.00	0.5058	0.0443

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
5.10	0.5092	0.0456
5.20	0.5148	0.0471
5.30	0.5229	0.0489
5.40	0.5336	0.0511
5.50	0.5468	0.0535
5.60	0.5624	0.0563
5.70	0.5803	0.0594
5.80	0.6002	0.0625
5.90	0.6219	0.0657
6.00	0.6449	0.0688
6.10	0.6690	0.0716
6.20	0.6937	0.0741
6.30	0.7187	0.0762
6.40	0.7436	0.0778
6.50	0.7680	0.0790
6.60	0.7917	0.0797
6.70	0.8143	0.0800
6.80	0.8356	0.0801
6.90	0.8554	0.0799
7.00	0.8735	0.0796
7.10	0.8899	0.0793
7.20	0.9044	0.0791
7.30	0.9171	0.0790
7.40	0.9280	0.0789
7.50	0.9371	0.0790
7.60	0.9447	0.0791
7.70	0.9507	0.0793
7.80	0.9553	0.0794
7.90	0.9587	0.0794
8.00	0.9611	0.0793
8.10	0.9627	0.0792
8.20	0.9635	0.0790
8.30	0.9638	0.0788
8.40	0.9637	0.0786
8.50	0.9633	0.0785
8.60	0.9628	0.0786
8.70	0.9622	0.0789
8.80	0.9616	0.0793
8.90	0.9611	0.0800
9.00	0.9606	0.0809
9.10	0.9603	0.0818
9.20	0.9601	0.0828
9.30	0.9601	0.0837
9.40	0.9601	0.0845
9.50	0.9602	0.0852
9.60	0.9603	0.0856
9.70	0.9604	0.0859
9.80	0.9605	0.0859
9.90	0.9605	0.0858
10.00	0.9604	0.0855

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
10.10	0.9602	0.0852
10.20	0.9599	0.0848
10.30	0.9594	0.0845
10.40	0.9588	0.0844
10.50	0.9582	0.0844
10.60	0.9574	0.0845
10.70	0.9566	0.0847
10.80	0.9558	0.0850
10.90	0.9550	0.0854
11.00	0.9542	0.0856
11.10	0.9537	0.0858
11.20	0.9533	0.0857
11.30	0.9531	0.0854
11.40	0.9532	0.0848
11.50	0.9537	0.0839
11.60	0.9546	0.0826
11.70	0.9559	0.0812
11.80	0.9576	0.0795
11.90	0.9599	0.0776
12.00	0.9626	0.0756
12.10	0.9658	0.0736
12.20	0.9696	0.0716
12.30	0.9740	0.0697
12.40	0.9788	0.0678
12.50	0.9842	0.0661
12.60	0.9901	0.0644
12.70	0.9965	0.0628
12.80	1.0033	0.0612
12.90	1.0107	0.0596
13.00	1.0185	0.0580
13.10	1.0267	0.0562
13.20	1.0354	0.0544
13.30	1.0444	0.0526
13.40	1.0539	0.0507
13.50	1.0637	0.0488
13.60	1.0739	0.0470
13.70	1.0844	0.0453
13.80	1.0952	0.0439
13.90	1.1064	0.0428
14.00	1.1178	0.0420
14.10	1.1294	0.0415
14.20	1.1413	0.0413
14.30	1.1533	0.0414
14.40	1.1653	0.0417
14.50	1.1775	0.0422
14.60	1.1895	0.0428
14.70	1.2015	0.0434
14.80	1.2132	0.0442
14.90	1.2246	0.0450
15.00	1.2357	0.0459

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
15.10	1.2462	0.0468
15.20	1.2562	0.0478
15.30	1.2655	0.0488
15.40	1.2740	0.0498
15.50	1.2816	0.0509
15.60	1.2884	0.0518
15.70	1.2942	0.0526
15.80	1.2990	0.0533
15.90	1.3027	0.0539
16.00	1.3055	0.0543
16.10	1.3074	0.0545
16.20	1.3083	0.0547
16.30	1.3085	0.0549
16.40	1.3080	0.0552
16.50	1.3069	0.0556
16.60	1.3054	0.0562
16.70	1.3038	0.0570
16.80	1.3020	0.0581
16.90	1.3004	0.0593
17.00	1.2992	0.0606
17.10	1.2984	0.0619
17.20	1.2982	0.0631
17.30	1.2988	0.0641
17.40	1.3003	0.0650
17.50	1.3027	0.0657
17.60	1.3060	0.0662
17.70	1.3103	0.0666
17.80	1.3155	0.0669
17.90	1.3214	0.0673
18.00	1.3280	0.0677
18.10	1.3350	0.0681
18.20	1.3423	0.0684
18.30	1.3497	0.0686
18.40	1.3570	0.0685
18.50	1.3639	0.0682
18.60	1.3703	0.0677
18.70	1.3761	0.0671
18.80	1.3812	0.0667
18.90	1.3855	0.0670
19.00	1.3890	0.0682
19.10	1.3920	0.0708
19.20	1.3945	0.0747
19.30	1.3968	0.0797
19.40	1.3991	0.0853
19.50	1.4018	0.0909
19.60	1.4052	0.0958
19.70	1.4095	0.0986
19.80	1.4150	0.1020
19.90	1.4217	0.1027
20.00	1.4296	0.1020

TABLE 2-2. FITTED FISSION CROSS-SECTIONS FOR NP-237

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
0.10	0.0246	0.0046
0.20	0.0383	0.0055
0.30	0.0816	0.0097
0.40	0.2203	0.0222
0.50	0.4499	0.0428
0.60	0.7341	0.0633
0.70	0.9707	0.0732
0.80	1.1542	0.0583
0.90	1.2789	0.0557
1.00	1.3598	0.0543
1.10	1.4099	0.0560
1.20	1.4429	0.0587
1.30	1.4696	0.0606
1.40	1.4972	0.0611
1.50	1.5289	0.0610
1.60	1.5647	0.0615
1.70	1.6025	0.0630
1.80	1.6389	0.0646
1.90	1.6706	0.0655
2.00	1.6948	0.0650
2.10	1.7096	0.0633
2.20	1.7145	0.0614
2.30	1.7100	0.0602
2.40	1.6974	0.0602
2.50	1.6790	0.0612
2.60	1.6570	0.0626
2.70	1.6338	0.0636
2.80	1.6115	0.0638
2.90	1.5915	0.0635
3.00	1.5749	0.0631
3.10	1.5620	0.0630
3.20	1.5528	0.0638
3.30	1.5466	0.0655
3.40	1.5425	0.0676
3.50	1.5393	0.0697
3.60	1.5359	0.0713
3.70	1.5313	0.0724
3.80	1.5246	0.0728
3.90	1.5154	0.0731
4.00	1.5033	0.0735
4.10	1.4886	0.0744
4.20	1.4717	0.0760
4.30	1.4534	0.0783
4.40	1.4346	0.0810
4.50	1.4165	0.0840
4.60	1.4001	0.0868
4.70	1.3866	0.0893
4.80	1.3769	0.0915
4.90	1.3719	0.0934
5.00	1.3722	0.0952

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
5.10	1.3782	0.0971
5.20	1.3900	0.0990
5.30	1.4075	0.1011
5.40	1.4304	0.1033
5.50	1.4580	0.1055
5.60	1.4897	0.1077
5.70	1.5247	0.1098
5.80	1.5621	0.1119
5.90	1.6011	0.1139
6.00	1.6408	0.1161
6.10	1.6805	0.1184
6.20	1.7194	0.1209
6.30	1.7571	0.1235
6.40	1.7932	0.1264
6.50	1.8273	0.1291
6.60	1.8593	0.1316
6.70	1.8893	0.1336
6.80	1.9173	0.1350
6.90	1.9435	0.1356
7.00	1.9682	0.1359
7.10	1.9915	0.1356
7.20	2.0137	0.1350
7.30	2.0351	0.1344
7.40	2.0560	0.1341
7.50	2.0765	0.1345
7.60	2.0966	0.1358
7.70	2.1165	0.1382
7.80	2.1361	0.1418
7.90	2.1553	0.1465
8.00	2.1741	0.1521
8.10	2.1923	0.1584
8.20	2.2096	0.1652
8.30	2.2259	0.1720
8.40	2.2410	0.1785
8.50	2.2547	0.1845
8.60	2.2668	0.1896
8.70	2.2773	0.1936
8.80	2.2861	0.1964
8.90	2.2931	0.1973
9.00	2.2983	0.1978
9.10	2.3020	0.1965
9.20	2.3042	0.1941
9.30	2.3050	0.1909
9.40	2.3047	0.1874
9.50	2.3036	0.1839
9.60	2.3017	0.1809
9.70	2.2995	0.1788
9.80	2.2969	0.1779
9.90	2.2944	0.1782
10.00	2.2919	0.1796

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
10.10	2.2897	0.1818
10.20	2.2879	0.1844
10.30	2.2864	0.1869
10.40	2.2853	0.1889
10.50	2.2846	0.1903
10.60	2.2843	0.1908
10.70	2.2841	0.1905
10.80	2.2841	0.1895
10.90	2.2841	0.1881
11.00	2.2841	0.1864
11.10	2.2839	0.1848
11.20	2.2835	0.1835
11.30	2.2828	0.1825
11.40	2.2817	0.1818
11.50	2.2802	0.1813
11.60	2.2785	0.1807
11.70	2.2763	0.1798
11.80	2.2740	0.1784
11.90	2.2714	0.1764
12.00	2.2687	0.1737
12.10	2.2661	0.1706
12.20	2.2635	0.1673
12.30	2.2611	0.1642
12.40	2.2590	0.1616
12.50	2.2572	0.1599
12.60	2.2559	0.1591
12.70	2.2550	0.1592
12.80	2.2546	0.1598
12.90	2.2547	0.1606
13.00	2.2553	0.1610
13.10	2.2565	0.1608
13.20	2.2582	0.1596
13.30	2.2604	0.1574
13.40	2.2632	0.1543
13.50	2.2666	0.1505
13.60	2.2706	0.1465
13.70	2.2754	0.1426
13.80	2.2809	0.1394
13.90	2.2874	0.1370
14.00	2.2949	0.1355
14.10	2.3037	0.1347
14.20	2.3137	0.1343
14.30	2.3253	0.1340
14.40	2.3384	0.1338
14.50	2.3532	0.1340
14.60	2.3698	0.1352
14.70	2.3880	0.1383
14.80	2.4078	0.1442
14.90	2.4292	0.1535
15.00	2.4518	0.1661

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
15.10	2.4754	0.1814
15.20	2.4997	0.1984
15.30	2.5241	0.2157
15.40	2.5483	0.2321
15.50	2.5717	0.2462
15.60	2.5938	0.2570
15.70	2.6142	0.2639
15.80	2.6323	0.2663
15.90	2.6477	0.2641
16.00	2.6601	0.2577
16.10	2.6693	0.2476
16.20	2.6750	0.2349
16.30	2.6774	0.2206
16.40	2.6766	0.2063
16.50	2.6728	0.1935
16.60	2.6664	0.1832
16.70	2.6579	0.1763
16.80	2.6480	0.1727
16.90	2.6372	0.1720
17.00	2.6263	0.1733
17.10	2.6159	0.1757
17.20	2.6066	0.1784
17.30	2.5989	0.1811
17.40	2.5934	0.1836
17.50	2.5902	0.1855
17.60	2.5895	0.1867
17.70	2.5914	0.1870
17.80	2.5955	0.1860
17.90	2.6016	0.1839
18.00	2.6093	0.1807
18.10	2.6180	0.1772
18.20	2.6271	0.1743
18.30	2.6361	0.1730
18.40	2.6445	0.1739
18.50	2.6520	0.1770
18.60	2.6580	0.1810
18.70	2.6627	0.1845
18.80	2.6659	0.1859
18.90	2.5678	0.1840
19.00	2.6687	0.1789
19.10	2.6691	0.1719
19.20	2.6693	0.1661
19.30	2.6699	0.1653
19.40	2.6712	0.1723
19.50	2.6735	0.1873
19.60	2.6769	0.2081
19.70	2.6815	0.2309
19.80	2.6870	0.2527
19.90	2.6931	0.2711
20.00	2.6993	0.2843

TABLE 2-3. FITTED FISSION CROSS-SECTIONS FOR TH-232

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
0.10	0.0	0.0
0.20	0.0	0.0
0.30	0.0	0.0
0.40	0.0	0.0
0.50	0.0	0.0
0.60	0.0	0.0
0.70	0.0	0.0
0.80	0.0	0.0
0.90	0.0	0.0
1.00	0.0014	0.0003
1.10	0.0030	0.0006
1.20	0.0061	0.0012
1.30	0.0129	0.0026
1.40	0.0406	0.0081
1.50	0.0825	0.0165
1.60	0.1046	0.0213
1.70	0.0982	0.0215
1.80	0.0861	0.0228
1.90	0.0895	0.0235
2.00	0.1068	0.0264
2.10	0.1222	0.0303
2.20	0.1244	0.0308
2.30	0.1154	0.0302
2.40	0.1058	0.0305
2.50	0.1038	0.0299
2.60	0.1101	0.0293
2.70	0.1195	0.0296
2.80	0.1265	0.0292
2.90	0.1288	0.0281
3.00	0.1284	0.0274
3.10	0.1287	0.0267
3.20	0.1312	0.0258
3.30	0.1352	0.0253
3.40	0.1386	0.0249
3.50	0.1400	0.0249
3.60	0.1395	0.0254
3.70	0.1387	0.0261
3.80	0.1391	0.0263
3.90	0.1411	0.0267
4.00	0.1437	0.0270
4.10	0.1455	0.0264
4.20	0.1454	0.0256
4.30	0.1441	0.0260
4.40	0.1428	0.0271
4.50	0.1426	0.0276
4.60	0.1439	0.0272
4.70	0.1456	0.0269
4.80	0.1463	0.0264
4.90	0.1451	0.0258
5.00	0.1424	0.0261

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
5.10	0.1397	0.0265
5.20	0.1383	0.0256
5.30	0.1385	0.0245
5.40	0.1392	0.0256
5.50	0.1387	0.0275
5.60	0.1365	0.0280
5.70	0.1335	0.0276
5.80	0.1326	0.0273
5.90	0.1365	0.0261
6.00	0.1460	0.0241
6.10	0.1599	0.0240
6.20	0.1760	0.0260
6.30	0.1931	0.0281
6.40	0.2125	0.0286
6.50	0.2364	0.0281
6.60	0.2649	0.0285
6.70	0.2941	0.0276
6.80	0.3181	0.0232
6.90	0.3338	0.0259
7.00	0.3439	0.0322
7.10	0.3532	0.0320
7.20	0.3609	0.0321
7.30	0.3604	0.0341
7.40	0.3543	0.0565
7.50	0.3462	0.0551
7.60	0.3375	0.0499
7.70	0.3300	0.0453
7.80	0.3246	0.0438
7.90	0.3215	0.0440
8.00	0.3201	0.0441
8.10	0.3198	0.0438
8.20	0.3197	0.0437
8.30	0.3192	0.0443
8.40	0.3177	0.0451
8.50	0.3151	0.0452
8.60	0.3114	0.0445
8.70	0.3068	0.0437
8.80	0.3016	0.0445
8.90	0.2964	0.0485
9.00	0.2914	0.0557
9.10	0.2870	0.0648
9.20	0.2835	0.0744
9.30	0.2809	0.0830
9.40	0.2794	0.0900
9.50	0.2789	0.0949
9.60	0.2791	0.0977
9.70	0.2799	0.0985
9.80	0.2810	0.0977
9.90	0.2823	0.0957
10.00	0.2834	0.0927

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
10.10	0.2841	0.0892
10.20	0.2844	0.0854
10.30	0.2842	0.0817
10.40	0.2834	0.0786
10.50	0.2821	0.0765
10.60	0.2803	0.0758
10.70	0.2781	0.0768
10.80	0.2758	0.0794
10.90	0.2735	0.0833
11.00	0.2713	0.0878
11.10	0.2694	0.0922
11.20	0.2678	0.0960
11.30	0.2668	0.0987
11.40	0.2663	0.0998
11.50	0.2665	0.0993
11.60	0.2672	0.0973
11.70	0.2685	0.0937
11.80	0.2703	0.0890
11.90	0.2725	0.0836
12.00	0.2752	0.0780
12.10	0.2782	0.0726
12.20	0.2815	0.0678
12.30	0.2849	0.0640
12.40	0.2885	0.0611
12.50	0.2923	0.0591
12.60	0.2961	0.0577
12.70	0.3001	0.0566
12.80	0.3041	0.0555
12.90	0.3083	0.0543
13.00	0.3126	0.0530
13.10	0.3171	0.0517
13.20	0.3218	0.0506
13.30	0.3267	0.0497
13.40	0.3317	0.0491
13.50	0.3369	0.0488
13.60	0.3422	0.0486
13.70	0.3476	0.0485
13.80	0.3530	0.0482
13.90	0.3584	0.0476
14.00	0.3637	0.0467
14.10	0.3688	0.0454
14.20	0.3737	0.0440
14.30	0.3783	0.0427
14.40	0.3826	0.0416
14.50	0.3867	0.0410
14.60	0.3904	0.0411
14.70	0.3939	0.0418
14.80	0.3973	0.0430
14.90	0.4006	0.0446
15.00	0.4041	0.0462

ENERGY(MEV)	SIGMA(BARNS)	DELTA SIGMA(BARNS)
15.10	0.4077	0.0478
15.20	0.4116	0.0491
15.30	0.4160	0.0499
15.40	0.4211	0.0504
15.50	0.4268	0.0504
15.60	0.4333	0.0500
15.70	0.4406	0.0493
15.80	0.4487	0.0483
15.90	0.4575	0.0471
16.00	0.4669	0.0460
16.10	0.4766	0.0451
16.20	0.4865	0.0446
16.30	0.4964	0.0446
16.40	0.5059	0.0454
16.50	0.5146	0.0468
16.60	0.5224	0.0488
16.70	0.5289	0.0511
16.80	0.5338	0.0535
16.90	0.5370	0.0556
17.00	0.5384	0.0571
17.10	0.5378	0.0580
17.20	0.5354	0.0579
17.30	0.5312	0.0571
17.40	0.5256	0.0555
17.50	0.5188	0.0536
17.60	0.5113	0.0517
17.70	0.5034	0.0504
17.80	0.4957	0.0503
17.90	0.4886	0.0515
18.00	0.4826	0.0542
18.10	0.4782	0.0578
18.20	0.4755	0.0620
18.30	0.4748	0.0661
18.40	0.4762	0.0698
18.50	0.4796	0.0726
18.60	0.4846	0.0743
18.70	0.4911	0.0746
18.80	0.4985	0.0736
18.90	0.5062	0.0712
19.00	0.5136	0.0676
19.10	0.5204	0.0635
19.20	0.5258	0.0596
19.30	0.5296	0.0574
19.40	0.5317	0.0581
19.50	0.5320	0.0621
19.60	0.5308	0.0687
19.70	0.5286	0.0763
19.80	0.5260	0.0832
19.90	0.5239	0.0860
20.00	0.5228	0.0896

TABLE 3. Comparison of Fission Spectrum Averaged Cross Sections ($\bar{\sigma}_f$)

Reaction	Authors (Reference given in parenthesis)	$\bar{\sigma}_f$ (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. 312. ± 5.	Measured 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
	Bresesti et al. 70 (3)	269.0	Calc. Watt-Spectrum
	Bresesti 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.
	Grundl 68 (63,4)	325. ± 19.	Measured
	Fabry et al. 70 (4)	374. ± 30.	Measured

- continued

TABLE 3. (continued)

Reaction	Authors (References)	$\bar{\sigma}_f$ (mb)	Remarks
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) = 313 mb
	Grundl 63 (58)	1370.	Calc. Maxwell-Spec.
	Grundl 63 (58)	1391.	Calc. Watt-Spec.
	Grundl 68 (63,4)	1365. ± 25.	Measured
	McElroy 69 (64)	1368.	Calc. SAND-II
	Hinkelmann 70 (65)	*1570.	Calc. Frye-Spec., 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 20 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.

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

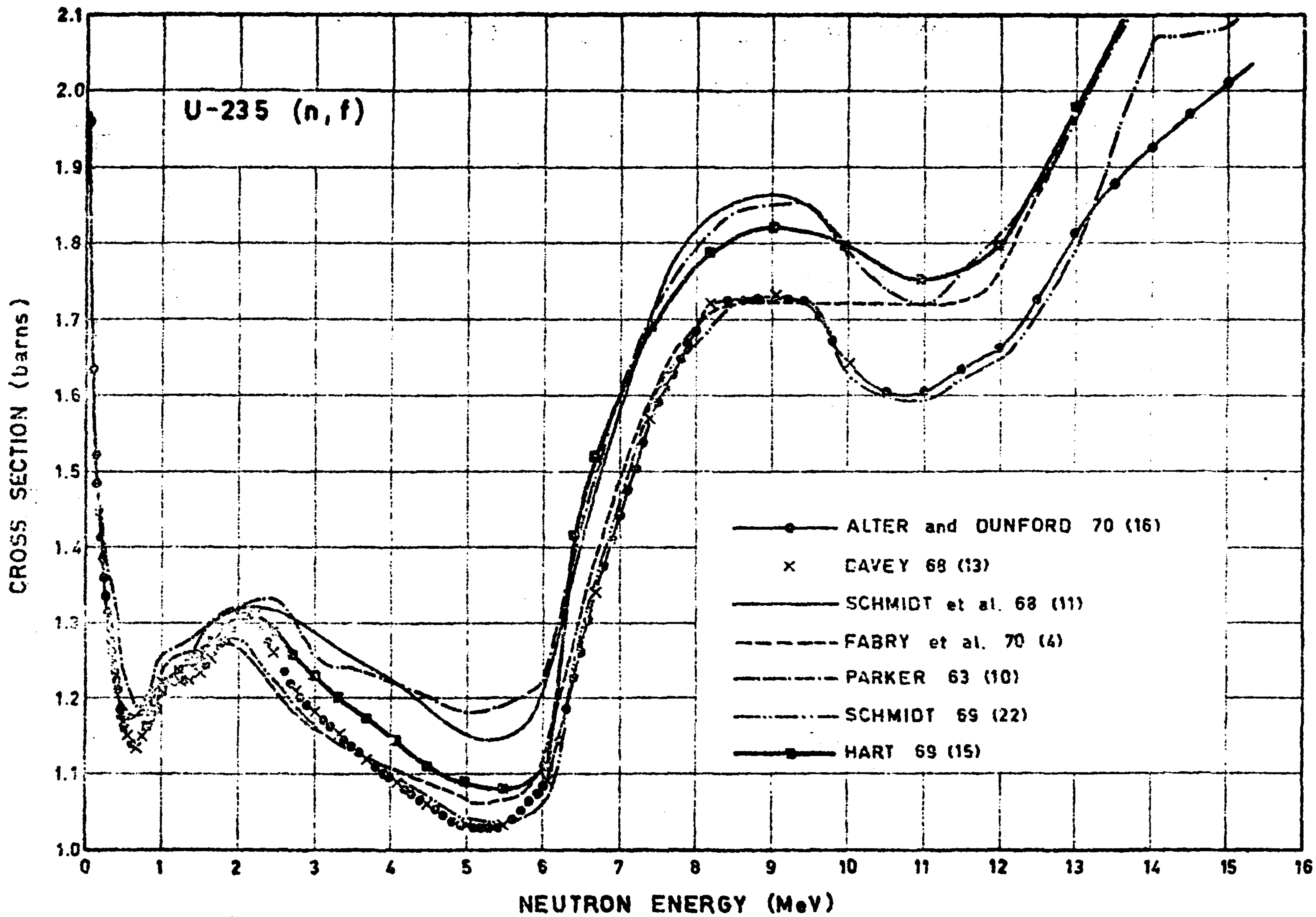

Fig. 1. EVALUATED U-235 FISSION CROSS SECTIONS

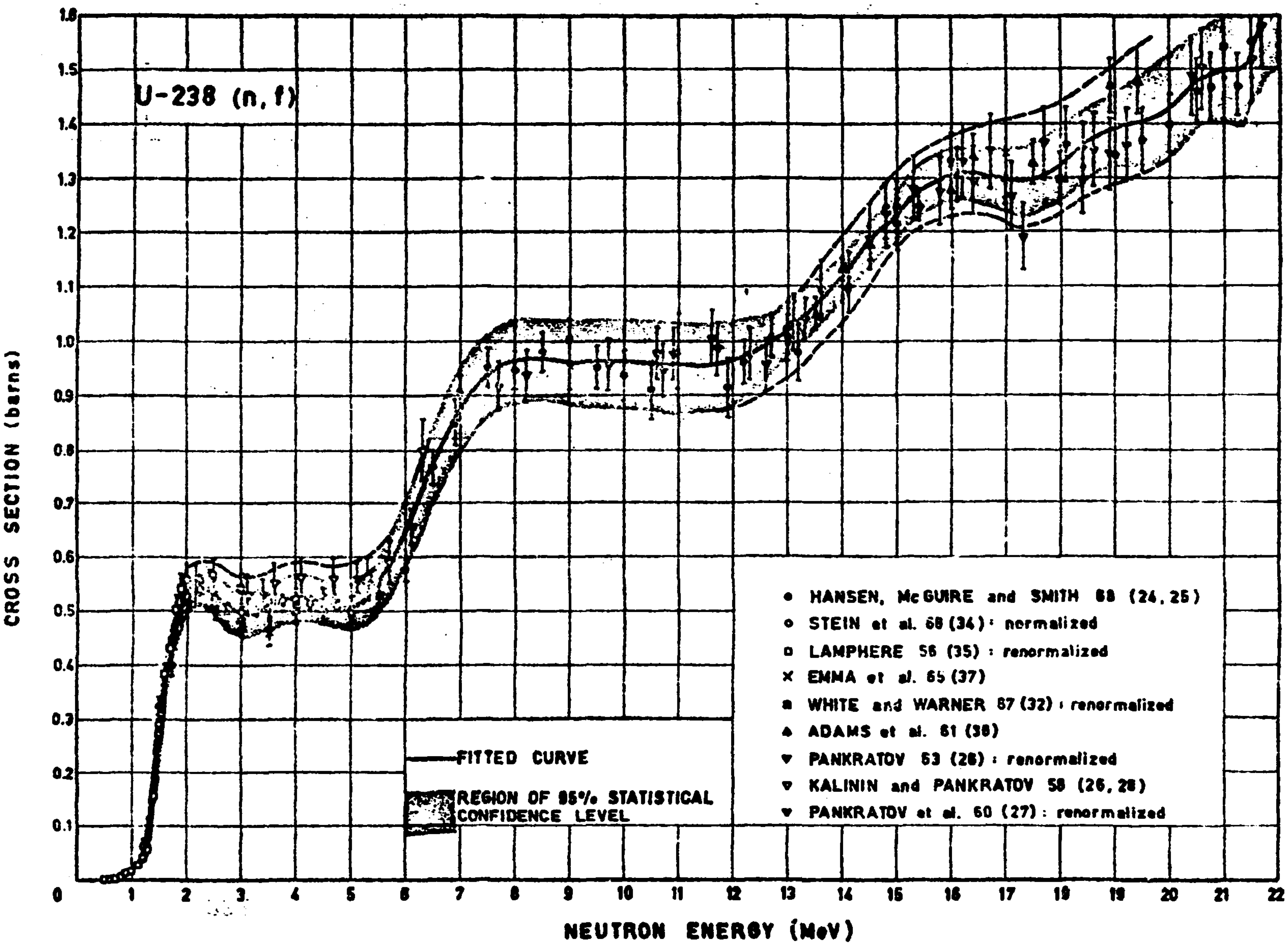

Fig. 2. U-238 (n, f) EXCITATION CURVE

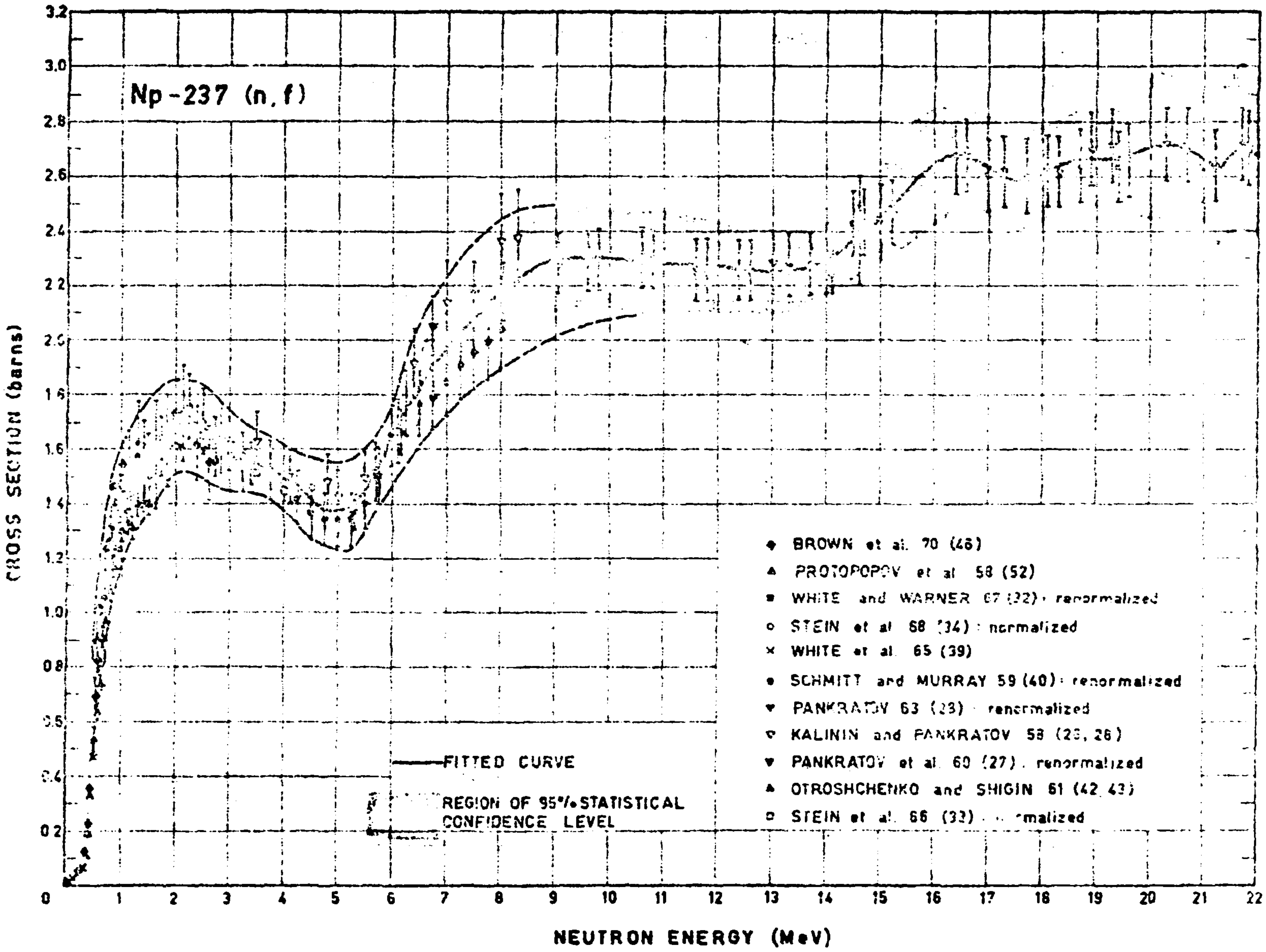

Fig. 3. Np-237 (n, f) EXCITATION CURVE

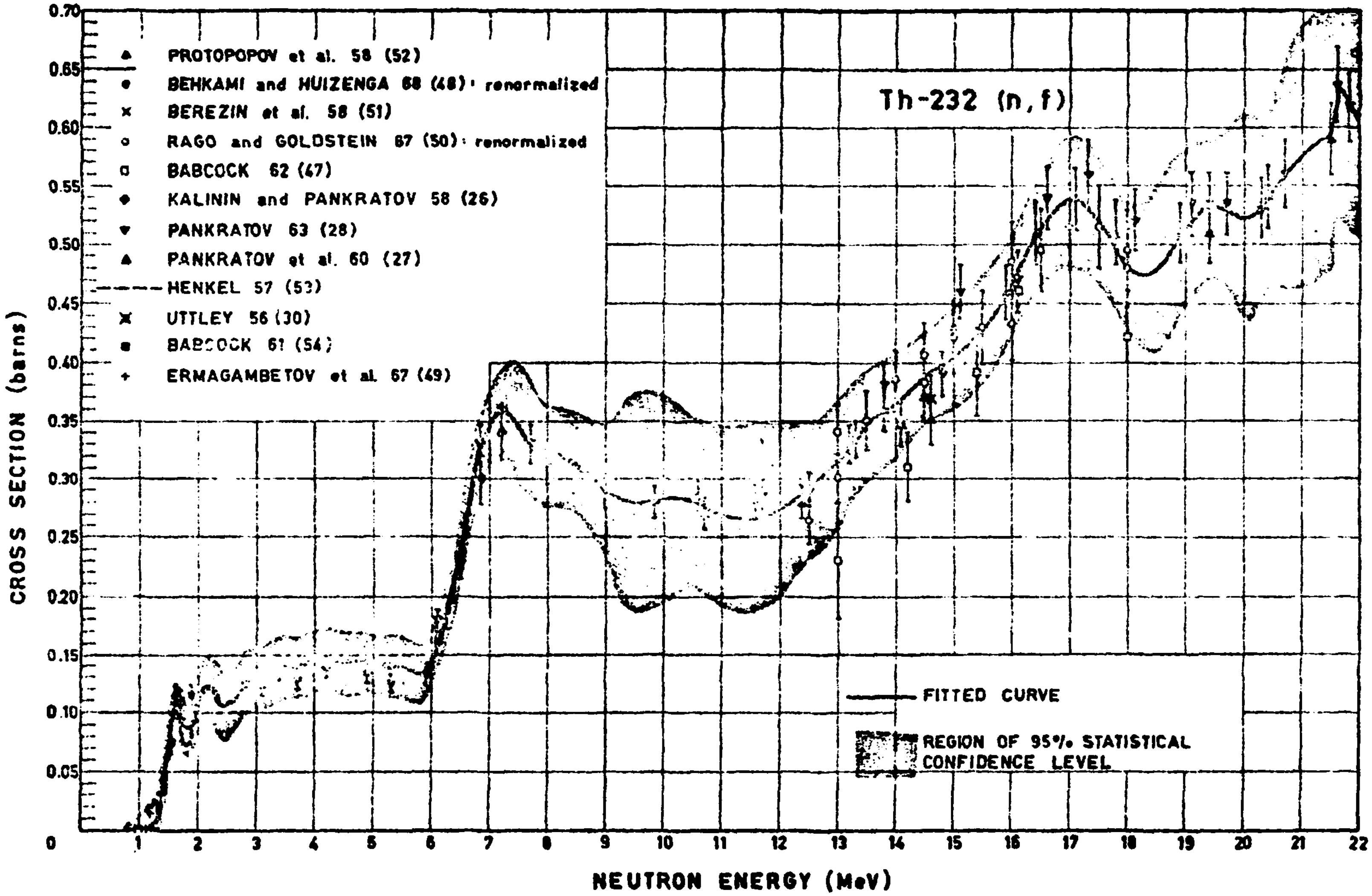

Fig. 4. Th-232 (n, f) EXCITATION CURVE