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Cf-252 Neutron Spectrum

Abstract: The californium-252 spontaneous fission neutron spectrum evaluated by W. Mannhart, PTB Braunschweig, Federal Republic of Germany, is documented. The numerical data are available on magnetic tape, costfree, from the IAEA Nuclear Data Section.

H.D. Lemmel (Ed.)

December 1987

Cf-252 Neutron Spectrum

The californium-252 spontaneous fission neutron spectrum was evaluated by W. Mannhart, Physikalisch-Technische Bundesanstalt Braunschweig, Federal Republic of Germany. The evaluation was performed following a recommendation of the International Nuclear Data Committee which then adopted this data set as an internationally recommended standard reference, for the time being.

The evaluation covers the energy range from 1 keV to 20 MeV. The data are given in an ENDF similar format, in two files.

The first file gives in MF=5 the data pointwise as function of energy, with the energy points chosen dense enough for logarithmic interpolation below 750 keV and linear interpolation above.

The second file gives in MF=35 the absolute covariance matrix of the neutron spectrum in 70 energy bins (ENDF-6 format). To allow the derivation of the relative covariance matrix, there is an "auxiliary file" which gives the spectrum averages of the 70 energy bins. With these data the correlation matrix shown in the "documentation file" can be derived.

Whereas the first file and MF=35 of the second file can be coded easily in proper ENDF format, it will have to be studied how the remainder of the second file can best be entered in ENDF-6 format. For the time being the data are kept as a separate data file without an accession-numbers (MAT-number).

The evaluation was described fully in a paper by W. Mannhart presented at the IAEA Meeting on Properties of Neutron Sources, Leningrad, USSR, 9-13 June 1986, published as IAEA-TECDOC-410, IAEA, 1987. This paper is attached.

The data files on magnetic tape were received in September 1987 at the IAEA Nuclear Data Section, where the record structure was changed from a PDP format to IBM standard.

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1. Reprint from IAEA-TECDOC-410

2. Listings of the two data files

3. Cf-252 spectrum averaged cross-sections presented by W. Mannhart at the 6th ASTM Symposium on Reactor Dosimetry, 31 May - 5 June 1987, Jackson Hole, WY, USA.

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PROPERTIES
OF NEUTRON SOURCES

PROCEEDINGS OF AN ADVISORY GROUP MEETING
ON PROPERTIES OF NEUTRON SOURCES
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND HELD IN
LENINGRAD, USSR, 9–13 JUNE 1986

EVALUATION OF THE Cf-252 FISSION NEUTRON SPECTRUM BETWEEN 0 MeV AND 20 MeV

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Abstract

The results of seven recent measurements of the Cf-252 neutron spectrum were used in the evaluation. Based on the available information, for each experiment a complete uncertainty covariance matrix was generated. The data were combined by generalized least-squares techniques. The evaluation was carried out with 70 energy grid points between 25 keV and 19.8 MeV. The individual experimental data were extrapolated to these grid points by using the shape of a Maxwellian distribution specific for each experiment. The evaluation gave a value of χ^2 per degree of freedom of approximately unity and indicated no incompatibility between the experiments. The resulting relative uncertainty of the evaluation is smaller than 2 % between 180 keV and 9.3 MeV. A weighted spline interpolation between the discrete data points was used to generate a continuous shape of the evaluated neutron spectrum. The result of the evaluation was compared with available theoretical descriptions of the Cf-252 neutron spectrum. None of the existing theories is compatible with the evaluation over the whole energy range.

1. Introduction

Measurements of the neutron spectrum of Cf-252 have been performed since 1955. In 1971/1972 the spectrum was defined as a standard /1, 2/ for neutron detector calibration and reactor dosimetry applications. Nevertheless, the shape of this neutron spectrum has not yet been unambigously defined. This discrepancy between definition and the actual state of the standard was a major problem for many years. A review of all experiments prior to 1979 /3/

reflects some of the difficulties. Historically based, most of the earlier experiments had been analyzed in terms of a Maxwellian. The resulting energy parameters showed a large spread in their value and were difficult to compare due to their restricted validity in different energy ranges. Another point which gave rise to problems was the wide energy range covered by this spectrum. Measurements of the Cf-252 neutron spectrum required the use of different kinds of neutron detectors to be able to cover the spectrum over the full energy range. In addition, many of the problems associated with the experimental determination of this spectrum have been recognized only recently /4/. Recent experiments performed with refined techniques and with improved corrections have therefore given more precise results. A comprehensive review of these post 1979 experiments is given elsewhere /5/. From time to time the status of the standard was discussed and temporary recommendations were given /6, 7/. The only systematic attempt to define the spectrum in its shape was an evaluation performed at the NBS /8/. This evaluation covered experiments before 1975 and stated piecemeal correction functions relative to a reference Maxwellian with an energy parameter of T = 1.42 MeV.

With improved experimental results and, at the same time, an increasing interest in describing the spectrum on a theoretical basis /9, 10/, the question of the adequacy of a Maxwellian in representing the spectrum lost its weight. It is todays' consensus that although the Maxwellian is convenient to scale experimental results, the shape of a Maxwellian is inappropriate for defining the Cf-252 neutron spectrum over a wider energy range.

Compared with the situation at the time of the NBS evaluation we now have the most favourable conditions. More experimental results obtained with improved techniques and a resulting higher precision are available and advanced evaluation methods based on generalized least-squares techniques /11, 12/ describe the present state-of-the-art. However, the last point in particular has produced a new class of problems in the form of documentation deficits. The new evaluation methods define obligatory requirements for the documentation of experimental data. Apart from comprehensive uncertainty listings, the correlations of the data, too, must be documented or sufficient details must be quoted to allow a deduction of these quantities.

Many of the older experiments lack a detailed description and it is sometimes necessary to re-analyze the data in order to take all corrections properly into account. This all results in serious restrictions, as it concerns the inclusion of such data into evaluations. The present evaluation had to be confined to more recent experiments where these problems have been, at least to some extent, circumvented.

2. Experimental data base

The data used in this evaluation comprise most of the post-1979 experiments. All of the experiments used were based on time-of-flight (TOF) techniques. A summary of the experiments is listed in Table 1. The energy range covered by each experiment and the number of available data points are given. A brief listing of a few characteristics of each experiment is given below.

Lajtai et al. /14/ (Fig. 1)

A flight path of (30.0 ± 0.1) cm was used for the experiment. The efficiency of the fission fragment detector was approximately 99 %. The neutron detector was a thick lithium glass scintillator (NE-912). The efficiency was experimentally measured relative to a thin lithium glass detector (NE-908). The efficiency of the thin detector was calculated using Monte Carlo methods.

The data of this experiment are plotted in Fig. 1 relative to a Maxwellian with an energy parameter of 1.42 MeV. This form of

Table 1: Experiments used in the evaluation

Authors	Energy range of the experiment	Number of data points
Lajtai et al. /14/	25 keV - 1.22 MeV	70
Böttger et al. /15/	2.00 MeV - 14.00 MeV	60
Poenitz/Tamura /16/	0.25 MeV - 9.25 MeV	51
Blinov et al. /17/	42 keV - 11.36 MeV	73
Boldeman et al. /18/ (Lithium glass)	124 keV - 2.66 MeV	28
Boldemann et al. /18/ (Plastic scintillator)	1.05 MeV - 14.25 MeV	59
Märten et al. /19/	3.89 MeV - 19.77 MeV	16
		Total: 357

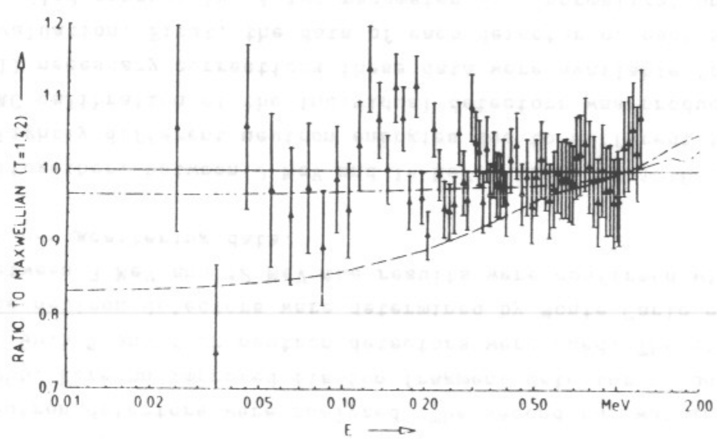

Fig. 1: Experimental data of Lajtai et al. /14/. Details in the text.

representation also used in the following figures has been recommended /6/. The figure also contains the curves of recently developed theories. The dashed line represents the theoretical data of Madland and Nix in the version presented at the Geel meeting /9/. This theory has been adjusted with the experimental data of Poenitz and Tamura /16/ between 0.25 MeV and 9.25 MeV. The dot-dashed curve represents the cascade evaporation model of Märten and Seeliger /10/ obtained with an anisotropy parameter of $\beta = 0.1$. The discontinuity of this curve at 1.8 MeV is due to a numerical error in the transmitted data and is without any physical consequences /13/.

Böttger et al. /15/ (Fig. 2)

This TOF experiment was based on a flight path of 12 m defined with an uncertainty of 0.24 cm. The experiment used three or four large volume NE-213 scintillation neutron detectors in parallel. It was performed in two separate runs. During the first period in August

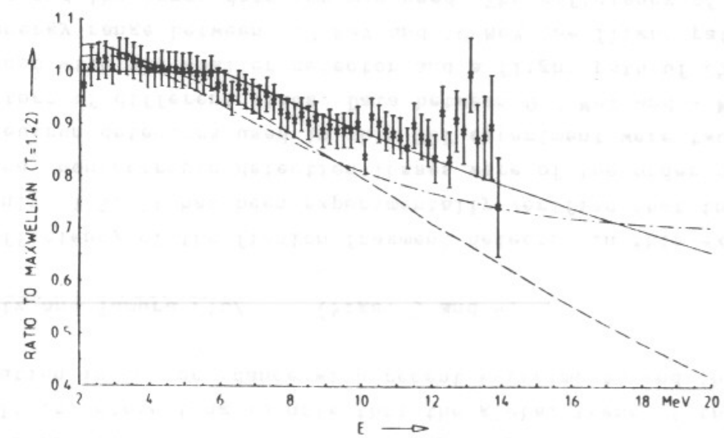

Fig. 2: Experimental data of Böttger et al. /15/. Details in the text.

1981 a fission fragment detector with an experimentally determined efficiency of 95.4 % was used. In this run the data of three neutron detectors were analyzed. The second run was in January 1986. Here an improved fission fragment detector of an efficiency of 99.5 % and four neutron detectors were used. The efficiencies of the neutron detectors were determined by Monte Carlo calculations. Between 3 MeV and 12 MeV the results were confirmed within $\pm$ 3 % by n-p scattering data.

Altogether, between 2 MeV and 14 MeV a total of 1018 data points at slightly different neutron energies due to different threshold and TAC calibration of the individual detectors was produced. Including all necessary corrections these data were available for the evaluation. First, the data of each detector of each series were handled separately. A two parameter fit (normalization constant and temperature parameter) with a Maxwellian was performed to obtain estimates of the energy-dependent shapes. Within the statistics the results for all detectors were identical. The shape parameters were used to transform the data of each detector from the individual energy grid to a common grid (steps of 200 keV between 2 MeV and 14 MeV) valid for all detectors. This process reduced the statistical uncertainties, whereas the systematic components remained unchanged and gave 420 data points. The common energy grid structure was the basis for further data compression. This was achieved step by step. First, the three detectors of run no. 1, then the four detectors of run no. 2 and finally the data of all seven detector sets were combined. In each step the compatibility of the data was tested. Within the uncertainties no inconsistencies between the different detectors and different series were found.

The 70 data points of this experiment finally obtained are plotted in Fig. 2. The representation in the figure is the same as in Fig. 1. However, the energy scale of this figure ranges from 2 MeV to 20 MeV. As in Fig. 1, the dashed curve corresponds to the theory of Madland and Nix /9/ and the dot-dashed curve represents the theoretical data of Märten and Seeliger /10/. The solid line above 6 MeV corresponds with the high-energy shape of the NBS evaluation /8/. It is interesting to note that the global trend of this old evaluation is in accordance with recent experiments and theories.

Poenitz and Tamura /16/ (Figs. 3 and 4)

The efficiency of the fission fragment detector in this experiment was only 71 %. It has been experimentally verified that the critical nonisotropic detection losses were of the order of 7 %. The neutron detectors used in this TOF experiment were two black detectors of different sizes. Data between 0.2 MeV and 4 MeV were obtained with the smaller detector and a flight path of 258 cm. In the energy range between 0.7 MeV and 10 MeV the flight path was 347 cm and the large detector was used. The efficiency of the smaller detector changed between 98 % and 83 %. For the large detector between 0.6 MeV and 10 MeV the corresponding efficiencies were between 96 % and 77 %. The uncertainty of the efficiency is very small and is of the order of 1 % to 2 %. The energy scale of the experiment has been verified with carbon resonances. The data of this experiment are plotted in Figs. 3 and 4.

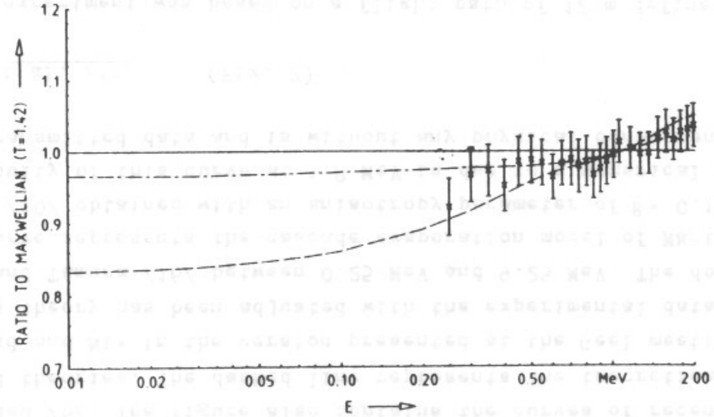

Fig. 3: Experimental data of Poenitz and Tamura /16/, below 2 MeV.

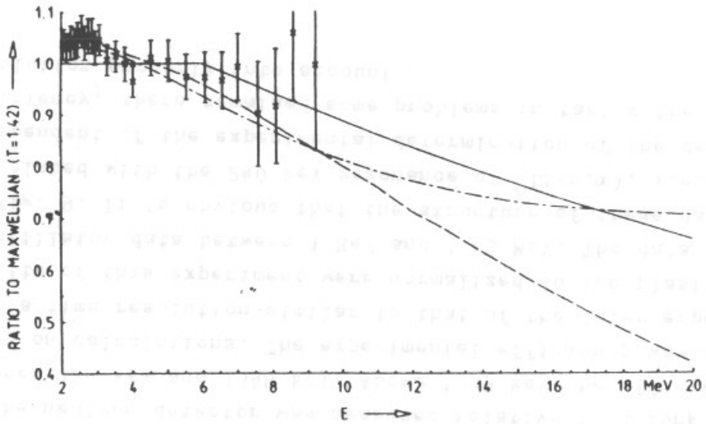

Fig. 4: Experimental data of Poenitz and Tamura /16/, above 2 MeV.

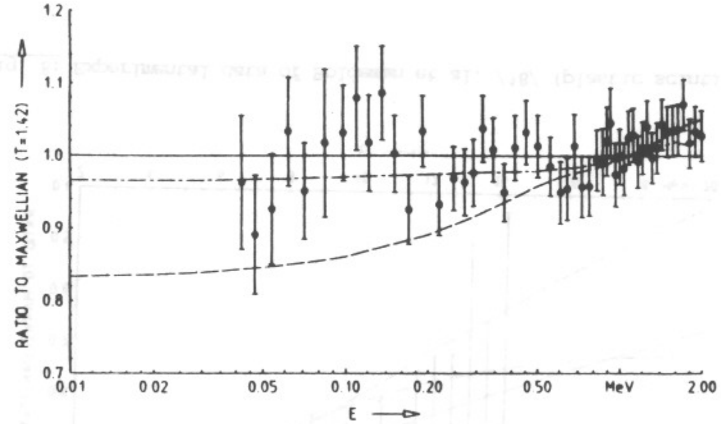

Fig. 5: Experimental data of Blinov et al. /17/, below 2 MeV.

Blinov et al. /17/ (Figs. 5 and 6)

The experiment was performed with different lengths of the flight path. The data used in the evaluation are based on a flight path of (50.00 ± 0.25) cm. The fission fragment detection efficiency was 99 %. A U-235 fission chamber acted as neutron detector. The efficiency of this chamber is proportional to the energy-dependent cross section of $^{235}U(n,f)$ and its uncertainty is given by the uncertainties of this cross section (ENDF/B-V). In the experiment, special attention was paid to calibrating the time scale precisely.

The authors prepared a comprehensive documentation of the experiment for the present evaluation. All corrections and the associated uncertainties were described in detail. The numerical data of this experiment are plotted in Figs. 5 and 6.

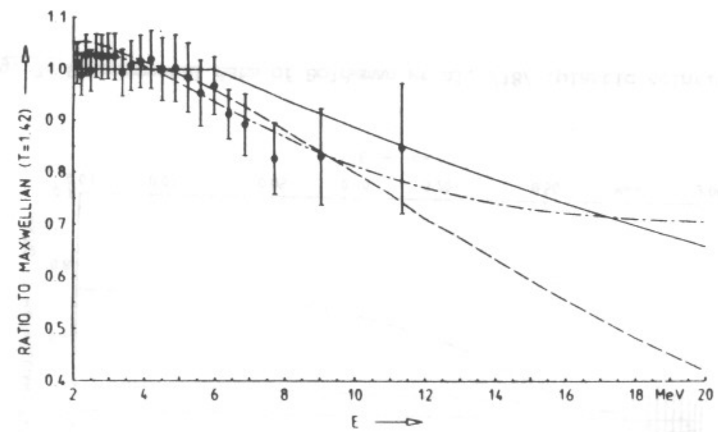

Fig. 6: Experimental data of Blinov et al. /17/, above 2 MeV.

Boldeman et al. /18/ (Figs. 7 and 8)

Data between 1 MeV and 15 MeV were measured with an NE-102 plastic scintillator as neutron detector and a flight path of 301.5 cm was used. The fission fragment detection efficiency was 97 %. Between 2 MeV and 11 MeV the efficiency of the neutron detector was experimentally determined using the associated particle method. The uncertainty is about 2 %. Between 1 MeV and 2 MeV the efficiency was measured relative to a long counter and above 11 MeV the efficiency is based on a Monte Carlo calculation which was tested between 2 MeV and 11 MeV. In all, seven different experiments were carried out. The data were combined by the authors and are plotted in Figs. 7 and 8.

Boldeman et al. /18/: ^{6}Li glass (Fig. 9)

In the low energy part of this experiment a lithium glass scintillator was used as neutron detector and a flight path of 40 cm. The fission fragment detector was the same. The efficiency of the neutron detector was measured relative to a long counter between 124 keV and 1349 keV. Above 1349 keV the efficiency is based on calculations. The experimental efficiency was determined with a time resolution similar to that of the later experiment. The results of this experiment were normalized to the plastic scintillator data between 1 MeV and 1.65 MeV. The data are plotted in Fig. 9. It is obvious that the structure of these data can be associated with the 240 keV resonance of ^{6}Li(n,α), i.e., independent of the experimental determination of the detector efficiency, there remained some problems in taking the time resolution properly into account.

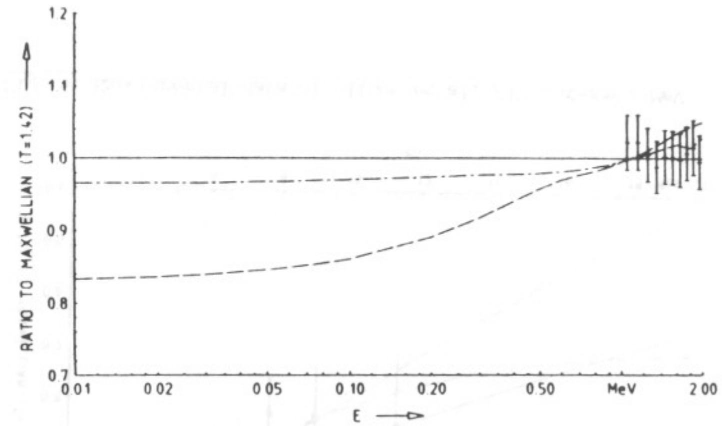

Fig. 7: Experimental data of Boldeman et al. /18/ (plastic scintillator)

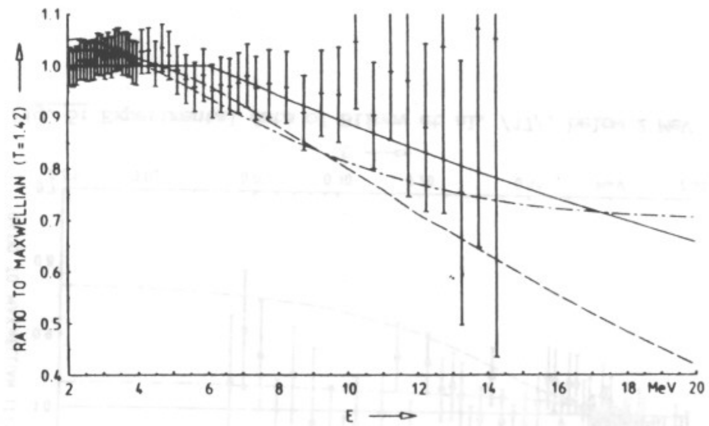

Fig. 8: Experimental data of Boldeman et al. /18/ (plastic scintillator)

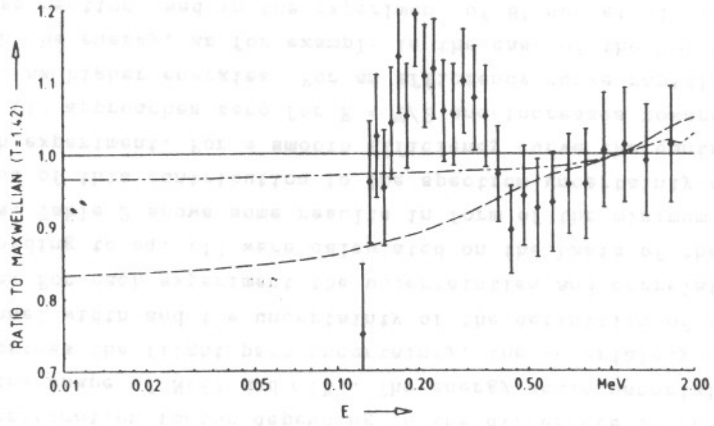

Fig. 9: Experimental data of Boldeman et al. /18/ (^{6}Li detector)

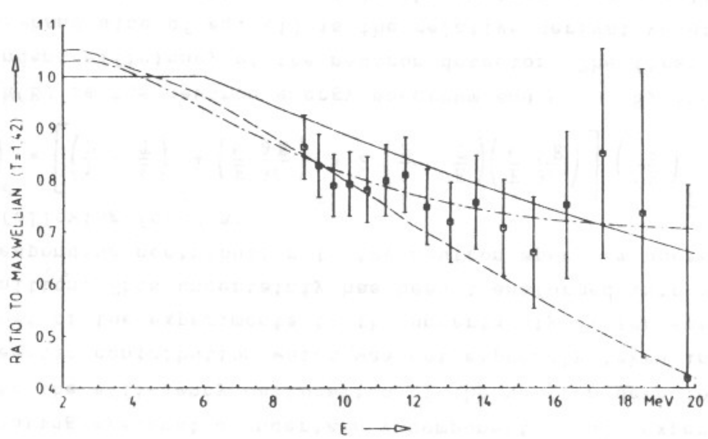

Fig. 10: Experimental data of Märten et al. /19/

Märten et al. /19/ (Fig. 10)

From this high energy experiment the data below 20 MeV were used. The fission fragment detection efficiency was 0.858 ± 0.010 derived from 0° to 90° measurements of the spectrum. The influence of the nonisotropic losses was corrected on the basis of angular distributions and theoretical models. A large NE-213 scintillator was the neutron detector. The flight path in the experiment was 450.0 cm. Similar to other experiments, pulse shape discrimination was used to reduce the background. The efficiency of the neutron detector was obtained from Monte Carlo calculations. The calculations have been checked with experiments between 4 MeV and 12 MeV by assuming the NBS evaluation /8/ as reference distribution. Above 12 MeV the efficiency is extrapolated. The uncertainty of the efficiency determination exceeds 5 % but the dominating uncertainty contributions in this experiment are from counting statistics, as can be seen from the data plotted in Fig. 10. The authors have prepared a detailed description of the experimental analysis for the present evaluation.

3. Steps of the evaluation process

An excellent review of all effects and corrections to be considered in sophisticated time-of-flight experiments is given in the paper of Poenitz and Tamura /16/ presented at the Antwerp conference. This information was used as a basis in checking the comprehensiveness of the analysis of the various experiments made use of in the present evaluation. Depending on the available documentation, no real deficits were identified. For all experiments, the calculation of the time resolution correction and the bin width correction has been repeated. Comparison of the present results with those expressly stated by the authors shows full agreement with the exception of the experiment of Boldeman et al. /18/ where the quoted time resolution correction factors were larger. This discrepancy may originate from an asymmetry in the time resolution function mentioned by the authors.

For each experimental data set, an uncertainty covariance matrix was generated, based on the documented uncertainty information and on additional information directly obtained from the authors. The dominating systematic uncertainty component of all experiments was due to the efficiency calibration of the neutron detectors. Another systematic contribution which was not expressly taken into account in most of the experiments is the uncertainty of the energy scale definition. This uncertainty has been transformed into a corresponding contribution to the neutron spectrum uncertainty with the following formula:

$$\left(\frac{\Delta N}{N}\right)^2 = \left[\left(\frac{1}{2} - \frac{E}{T}\right)^2 + \left(\frac{E}{\varepsilon}\frac{\partial \varepsilon}{\partial E}\right)^2 + 2\left(\frac{1}{2} - \frac{E}{T}\right)\left(\frac{E}{\varepsilon}\frac{\partial \varepsilon}{\partial E}\right)\right]\left(\frac{\Delta E}{E}\right)^2 \tag{1}$$

$N = N(E)$ is the neutron energy spectrum and $\varepsilon = \varepsilon(E)$ the energy-dependent efficiency of the neutron detector. The first term on the right-hand side of eq. (1) is the relative derivative of the neutron spectrum with respect to the neutron energy valid for a Maxwellian with a temperature parameter T. (For the present purpose this approximation in describing the spectrum by a Maxwellian is of minor influence). The second term in the formula is the corresponding derivative of the detector efficiency. The third term is an interference term which enhances or decreases the transformation factor depending on the difference in the direction of the shape of N(E) and ε(E). The energy scale uncertainty comprises the flight path uncertainty, the uncertainty of the time channel width and the uncertainty of the definition of the zero time. For each experiment the uncertainties and correlations according to eq. (1) were calculated on the basis of the available data. Table 2 shows some results in form of the minimum and maximum value of this contribution to the spectrum uncertainty specific to each experiment. For a smooth efficiency curve the contribution of eq. (1) approaches zero for E = T/2 and increases towards lower as well as higher energies. For an efficiency curve rapidly changing with the energy, as for example in the case of the U-235 fission cross section used in the experiment of Blinov et al. /17/, the result of eq. (1) fluctuates strongly in some energy regions.

Table 2: Magnitude of the energy scale uncertainty contribution

Authors	Minimum value	Maximum value
Lajtai et al.	0.0 %	1.3 %
Böttger et al.	0.1 %	1.7 %
Poenitz/Tamura	0.0 %	1.7 %
Blinov et al.	0.0 %	13.4 %
Boldeman et al. (Lithium glass)	0.0 %	5.9 %
Boldeman et al. (Plastic scintillator)	0.2 %	13.2 %
Märten et al.	3.8 %	9.2 %

To obtain a common basis for the evaluation a fixed energy grid was established. The selection of the grid point energies was governed by the density of the available data points as well as by the necessity to represent the structure of the spectrum adequately. Altogether, 70 grid point energies were chosen. Each of the original data points was transformed to the neighbouring energy grid point. Before doing this, the approximate slope of the data was determined. This was done by fitting a Maxwellian to the original data of each experiment. The results of these fits are summarized in Table 3. Two parameters were obtained from the fit procedure: a normalization constant and an energy parameter. Both quantities were highly correlated or anticorrelated. All these fits were made over the whole energy range of each experiment (see Table 1) without differentiating in certain energy ranges. The strong variation of the individual temperature parameters and the values of chi-square per degree of freedom indicating inconsistency between experimental data and the Maxwellian were of minor importance because information of Table 3 was only used for auxiliary purposes. The specific Maxwellian of each experiment was

Table 3: Two parameter fit of a Maxwellian to the experimental data

Authors	Normalization factor	T (MeV)	χ^2/f
Lajtai et al.	1.009 ± 0.041	1.430 ± 0.044	0.48
Böttger et al.	1.054 ± 0.004	1.379 ± 0.002	3.09
Poenitz/Tamura	1.010 ± 0.004	1.429 ± 0.005	1.16
Blinov et al.	0.993 ± 0.005	1.395 ± 0.004	1.25
Boldeman et al. (Lithium glass)	0.976 ± 0.012	1.365 ± 0.014	4.13
Boldeman et al. (Plastic scintillator)	1.010 ± 0.001	1.410 ± 0.002	3.26
Märten et al.	0.984 ± 0.097	1.372 ± 0.018	0.24

Table 4: Shape experiments in the evaluation

Authors	Normalization by the authors	Integral Maxwellian	Normalization factor of the evaluation
Poenitz/Tamura	0.25MeV -9.25MeV Maxw. T=1.42 MeV	94.6 %	1.007 ± 0.013
Blinov et al	40 keV - 10 MeV Maxw. T=1.42 MeV	99.4 %	0.997 ± 0.009
Boldeman et al. (Lithium glass)	with plastic scintillator data between 1MeV and 1.65MeV	-	1.009 ± 0.024
Boldeman et al. (Plastic scintillator)	none	-	1.010 ± 0.012

applied in the transformation of a data point from its original energy to the grid energy. Due to small shifts in energy the uncertainty contribution of this procedure was almost negligible and the original structure of each data set, shown in the Figs. 1 to 10, was not essentially changed.

Based on the common energy grid, the data sets were combined by generalized least-squares techniques with regard to their uncertainties. The evaluation has been made with absolute data, i.e. without the scaling used in the figures. However, some of the data sets had to be regarded as shape data. These sets are listed in Table 4. Poenitz and Tamura /16/ as well as Blinov et al. /17/ normalized their result to the numerical value of the integral of a Maxwellian with T = 1.42 MeV taken over the energy range of the experiment. The energy range applied and the value of the integral are given in Table 4. The data of Boldeman et al. /18/ obtained with the lithium glass detector have been normalized to his plastic scintillator data in an overlap energy range. All these normalizations were ignored and the data were taken as shape data. The final normalization was part of the evaluation process. Because of a poor documentation of the efficiency calibration procedure, the second data set of Boldeman et al. obtained with the NE-102 neutron detector has also been regarded as a shape data set instead of an absolute one. In the last column of Table 4 the final normalization factors obtained from the evaluation process are listed.

4. Results and discussion

The evaluation resulted in a chi-square value of 264.5 which must be compared with 265 degrees of freedom. From a first glance at the different data sets shown in Figs. 1 to 10, one might have anticipated difficulties in obtaining a consistent result. The chi-square value indicating a full compatibility between the different data sets was therefore rather surprising. However, this result demonstrates that a mathematically consistent data combination procedure with full regard to the uncertainties and correlations is superior to any eye-guided evaluation.

During the evaluation process a few difficulties arose. Nine of the seventy data points of the experiment of Lajtai et al. /14/ increased the chi-square contribution of this experiment by more than a factor of 4 and indicated a strong inconsistency with the remaining data from other experiments. These data points at neutron energies between 125 keV and 305 keV were within the range of the width of the broad ^{6}Li(n,α) resonance at 240 keV. Difficulties in the handling of this resonance in the neutron detector efficiency calibration cannot be excluded. However, it was not understood why other data points at neighbouring neutron energies of the same range exhibited no problems. It has nevertheless been decided to remove these nine points from the evaluation set. The same has also been done with six data points of the lithium glass set of Boldeman et al. /18/ where similar problems were more obvious and have already been discussed in section 2. Finally, 3 of the 59 data points in the data set of Boldeman et al. /18/, measured with the plastic scintillator detector, made the same contribution to the chi-square as the remainder of these data. It was impossible to find a physical explanation of this, neither was it possible to have recourse to the original measurements, as the only data available was that which had already been combined. Here, the somewhat arbitrary opinion of the evaluator was the only justification for the rejection of these three data points. In all, 18 of the 357 data points available were neglected in the evaluation process.

The result of the evaluation at discrete neutron energies is plotted in Figs. 11 and 12. The representation is the same as in Figs. 1 and 2. The error bars given were obtained from the diagonal elements of the final covariance matrix of the present evaluation. These data represent the state of the available experimental data base and therefore a totally smooth behaviour as function of the neutron energy cannot be expected. Between 180 keV and 9.3 MeV the resulting relative uncertainty of the evaluated data is smaller than 2 %. Between 45 keV and 150 keV and between 9.8 MeV and 13.3 MeV the corresponding value remains smaller than 5 %. The evaluated data point at 25 keV has a relative uncertainty of 10 % and above 13.3 MeV the uncertainty increases strongly up to 77 % for the data point at 19.8 MeV.

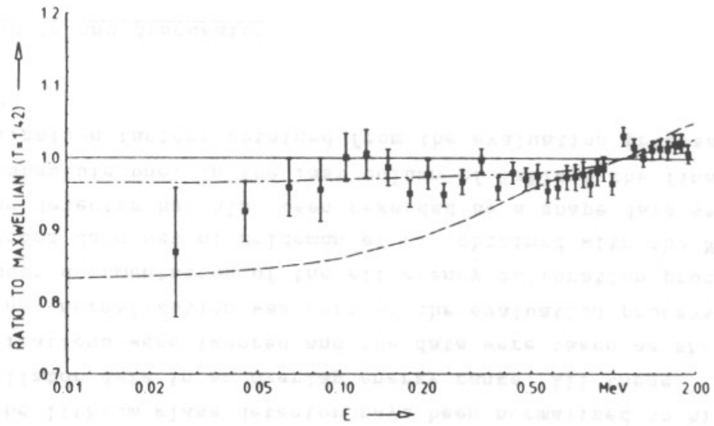

Fig. 11: Result of the evaluation at discrete neutron energies

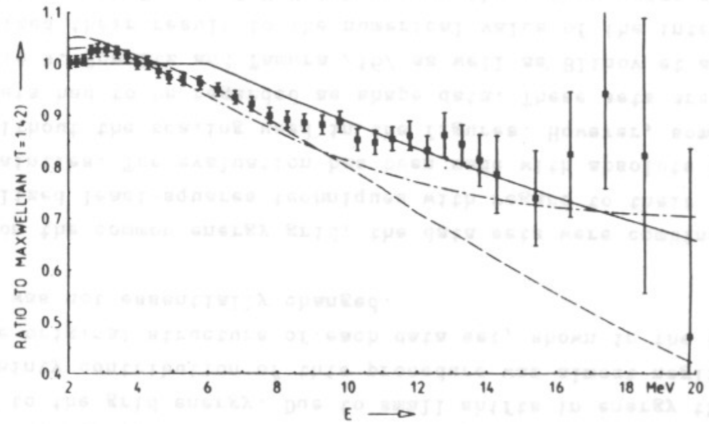

Fig. 12: Same as in Fig. 11, above 2 MeV.

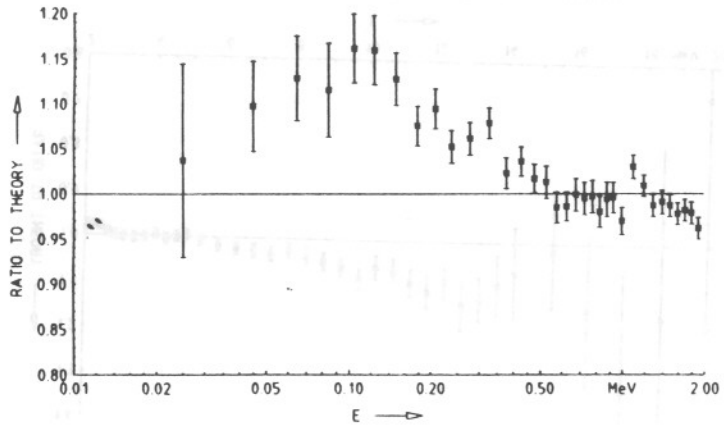

Fig. 13: Ratio of the evaluation relative to the theory of Madland and Nix /9/

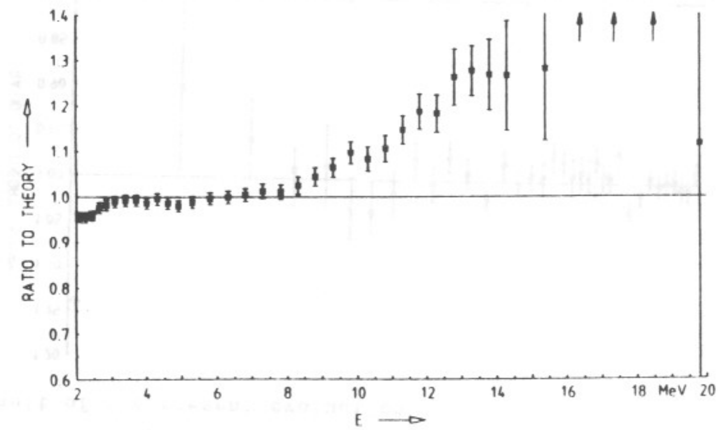

Fig. 14: Same as in Fig. 13, above 2 MeV.

The high accuracy of the evaluated data allowed differentation among some of the theoretical models. In the Figs. 13 and 14 the evaluated data are plotted relative to the theoretical model of Madland and Nix /9/ which is based on an adjustment to the experimental data of Poenitz and Tamura /16/. Below 0.4 MeV and above 8 MeV the theory underestimates the evaluated neutron spectrum. Above 11 MeV the deviation is larger than 10 %. Between 1 MeV and 3 MeV a slight overestimation of the theory can be identified. It cannot be excluded that a re-adjustment of this theory to the present evaluated data changes the global picture. However, it must still be proved if the level density parameter, the adjustable quantity of this theory, remains within physically reasonable limits.

The second theory used in this comparison is without freely adjustable parameters. The cascade evaporation model developed by Märten and Seeliger /10/ is based on a more detailed description of the physical processes and avoids some of the approximations used elsewhere /9/. The result used here is that with an anisotropy parameter of $\beta = 0.1$. In Figs. 15 and 16 the ratio of the evaluated data relative to this model is plotted. An overall agreement with the present data is given between 25 keV and 6 MeV. Above this energy the theoretical data is somewhat lower than the evaluated data, but the difference never exceeds 10 %. Recent improvements to this theory /20/ make it probable that these differences at high neutron energies can be further reduced.

At present, neither theory is adequate to describe within the uncertainties the evaluated data over the whole energy range. To obtain a smooth curve for the evaluated neutron spectrum a spline interpolation procedure was applied. This procedure used the variances of the evaluated neutron spectrum data at discrete energies as weights and generated a continous curve through the data points. The spline procedure has been applied to the complete data set between 25 keV and 19.8 MeV without any attempt to interpolate between partial energy ranges. The result is plotted in Figs. 17 and 18 relative to a reference Maxwellian with T = 1.42 MeV in the form of a continuous curve. In addition, the data at the discrete energies are given. This curve represents the real final result of the present evaluation.

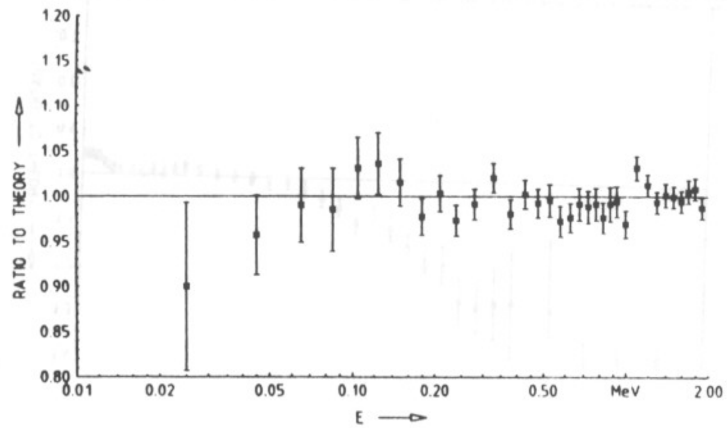

Fig. 15: Ratio of the evaluation relative to the theory of Märten and Seeliger /10/

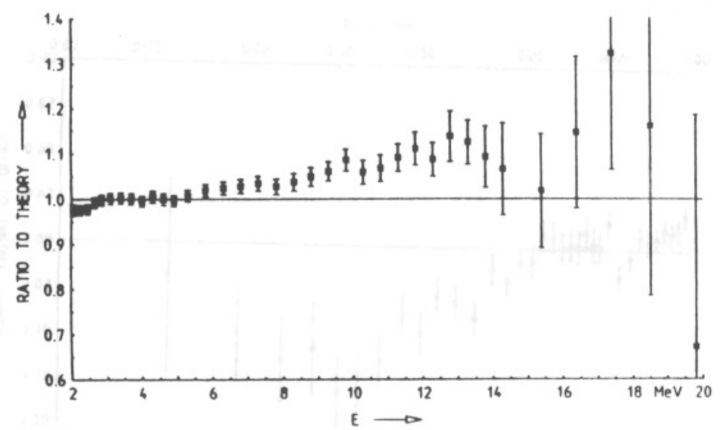

Fig. 16: Same as in Fig. 15, above 2 MeV.

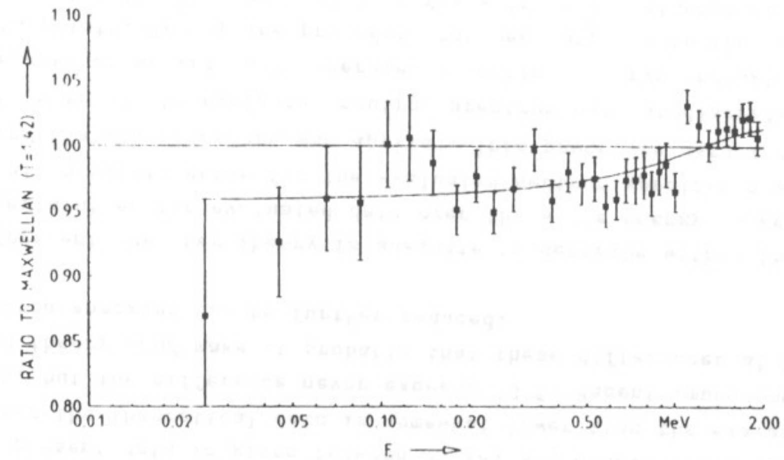

Fig. 17: Spline interpolated continuous form of the evaluation

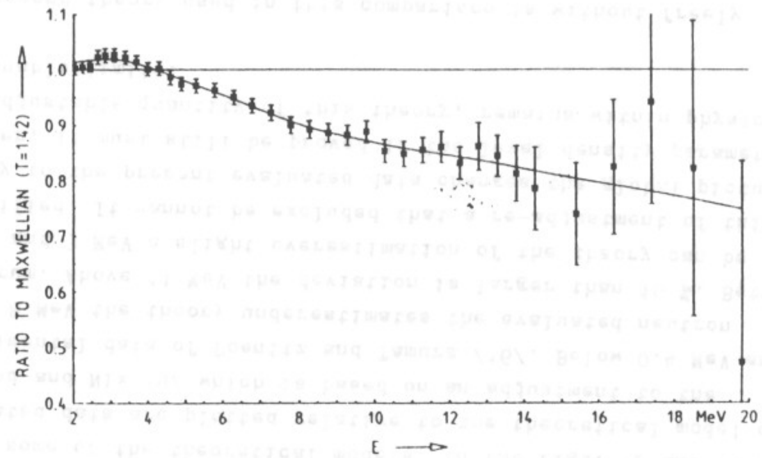

Fig. 18: Same as in Fig. 17, above 2 MeV.

5. Conclusions and future prospects

The neutron spectrum of spontaneous fission of Californium-252 has been evaluated on the basis of data of recent time-of-flight experiments. The result defines the spectrum with a precision never before obtained and supports the status of this spectrum as a standard. With the aim of further improving knowledge of this spectrum, in the near future it is planned to combine additional experimental data, especially the results of integral experiments and of recent TOF experiments performed at very high neutron energies, with the present evaluation.

The results of integral experiments (spectrum-averaged cross section data) have already been used in a preliminary evaluation of the Cf-252 neutron spectrum /21/. Instead of point-wise data, this evaluation yielded energy integrals over the spectral distribution. A comparison of these preliminary data /21/ with the present evaluation shows agreement within the uncertainties. The integral data were not considered in the present evaluation as this would have made necessary time consuming data transformation procedures which did not fit into the schedule of this work.

In addition, the analysis of two recent TOF experiments /22, 23/, which investigated the neutron spectrum up to 30 MeV, has not yet been finalized. The data of both experiments obtained below 20 MeV are believed to establish a sound basis for the reduction of the large uncertainties of the present evaluation between 14 MeV and 20 MeV. Both data sets are expected to be available very soon.

Before the end of 1986, the final version of the evaluation comprising the neutron spectrum and its covariance matrix will be released and transmitted to the Nuclear Data Section of the IAEA, for distribution to nuclear data centers.

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CALIFORNIUM-252 NEUTRON SPECTRUM

EVALUATED BY
WOLF MANNHART
PTB BRAUNSCHWEIG

DATE : JUNE 1987

****
****

FILE 5

ENERGY IN MEV
N(E) IN 1/MEV

```
INTERPOLATION: 1 KEV TO  0.75 MEV    LN¢N(E)! LINEAR IN LN¢E!
               0.75 MEV TO 20 MEV    LN¢N(E)! LINEAR IN E

HEADER:
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*********************************************************************
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              STRUCTURE OF THIS FILE IS IDENTIC
              WITH LB = 5 (RELATIVE MATRIX)

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  LS    LB   NT    NE

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-5.15876E-11	-1.81419E-11	-2.67743E-11	-1.35019E-11	-6.10721E-11	-5.38469E-12
-2.25095E-12	2.39003E-12	6.92932E-12	1.67143E-07	1.00178E-07	5.88793E-08
3.56087E-08	2.52781E-08	1.58250E-08	1.72370E-08	1.25146E-08	7.39014E-09
5.47486E-09	3.76646E-09	2.90145E-09	2.34560E-09	1.57491E-09	1.14884E-09
7.44458E-10	4.84540E-10	2.55065E-10	3.27385E-10	2.24468E-10	1.30494E-10
6.96244E-11	6.42411E-11	3.41709E-11	3.18497E-11	6.13111E-11	1.44897E-11
2.25528E-11	7.24128E-12	7.58497E-12	1.15933E-07	6.03280E-08	3.62674E-08
2.46287E-08	2.03084E-08	1.61770E-08	1.30502E-08	8.07870E-09	5.94956E-09
4.18470E-09	3.17443E-09	2.54813E-09	1.75395E-09	1.28692E-09	8.80463E-10
5.09273E-10	4.46258E-10	3.32356E-10	2.37436E-10	1.46262E-10	9.57826E-11
7.73522E-11	7.53852E-11	5.45082E-11	5.17529E-11	3.09934E-11	6.50487E-12
6.10371E-12	6.37615E-12	8.28731E-08	5.05509E-08	3.34149E-08	2.07470E-08
2.53329E-08	1.83284E-08	1.16387E-08	8.05799E-09	6.22833E-09	4.95247E-09
3.64193E-09	2.57880E-09	1.88788E-09	1.24941E-09	9.66078E-10	6.51165E-10
4.76440E-10	3.08017E-10	2.28694E-10	1.35552E-10	1.03735E-10	7.12252E-11
6.60784E-11	1.06685E-10	1.98548E-11	2.00812E-11	7.72414E-12	6.19122E-12
7.12557E-08	4.57983E-08	2.80076E-08	3.34726E-08	2.25877E-08	1.52630E-08
1.08526E-08	8.22502E-09	6.33420E-09	4.48302E-09	3.32702E-09	2.51835E-09
1.74030E-09	1.19275E-09	9.12413E-10	6.61047E-10	4.50789E-10	3.28795E-10
1.74256E-10	1.45654E-10	1.01256E-10	8.66488E-11	1.28382E-10	3.10102E-11
2.34673E-11	1.04485E-11	6.52140E-12	5.27680E-08	3.23864E-08	3.15230E-08
2.21315E-08	1.51904E-08	1.08534E-08	7.93466E-09	6.06000E-09	4.32112E-09
3.19698E-09	2.40479E-09	1.61694E-09	1.11601E-09	8.46606E-10	6.12296E-10
3.96000E-10	3.05000E-10	2.04822E-10	1.48831E-10	1.07282E-10	8.07512E-11
1.17639E-10	3.90981E-11	2.13713E-11	9.79288E-12	5.79709E-12	3.53112E-08
4.17880E-08	2.50620E-08	1.72157E-08	1.15562E-08	8.11270E-09	5.99281E-09
4.11876E-09	3.12991E-09	2.28329E-09	1.61942E-09	1.18098E-09	8.05548E-10
5.60220E-10	4.07485E-10	2.68017E-10	1.80741E-10	1.49160E-10	7.59100E-11
9.27700E-11	1.02313E-10	2.66937E-11	1.85045E-11	1.32686E-11	4.96634E-12
7.31095E-08	4.51092E-08	2.58899E-08	1.76311E-08	1.29594E-08	9.35406E-09
6.64198E-09	4.78257E-09	3.47737E-09	2.53047E-09	1.69517E-09	1.26764E-09
9.13856E-10	6.41914E-10	4.64478E-10	3.28931E-10	2.22675E-10	1.62874E-10
1.28312E-10	1.61236E-10	5.40524E-11	2.89047E-11	1.98794E-11	7.43301E-12
3.73763E-08	2.21623E-08	1.39750E-08	9.55864E-09	6.89867E-09	4.70953E-09
3.46809E-09	2.58108E-09	1.79577E-09	1.20109E-09	9.26667E-10	6.88251E-10
4.55233E-10	3.29509E-10	2.20100E-10	1.74310E-10	1.15470E-10	9.10210E-11
1.14309E-10	3.82948E-11	2.05098E-11	1.41653E-11	5.30115E-12	2.24735E-08
1.36385E-08	8.04177E-09	5.50721E-09	3.92414E-09	2.77191E-09	1.97265E-09
1.40065E-09	9.90046E-10	7.18844E-10	5.17927E-10	3.51801E-10	2.72734E-10
1.96237E-10	1.32803E-10	9.86435E-11	7.27909E-11	9.16204E-11	3.07772E-11
1.63848E-11	1.11324E-11	4.14662E-12	1.26420E-08	7.41545E-09	4.58152E-09
3.12892E-09	2.21674E-09	1.61100E-09	1.12842E-09	7.65218E-10	5.97976E-10
4.10032E-10	2.99220E-10	2.09908E-10	1.50912E-10	1.06805E-10	7.58810E-11
5.61557E-11	7.94209E-11	2.73480E-11	1.73147E-11	8.47922E-12	3.15410E-12
7.73412E-09	4.31478E-09	2.64949E-09	1.82216E-09	1.30109E-09	8.95380E-10
6.35573E-10	4.72652E-10	3.40410E-10	2.36969E-10	1.66534E-10	1.14630E-10
8.15669E-11	6.02896E-11	4.47184E-11	6.29004E-11	2.16707E-11	1.00527E-11
6.68395E-12	2.46259E-12	4.28273E-09	2.58581E-09	1.59955E-09	1.06932E-09
7.32976E-10	4.84686E-10	3.74972E-10	2.70026E-10	1.90064E-10	1.30549E-10

9.49552E-11	6.69392E-11	4.82862E-11	3.69313E-11	4.77901E-11	1.64648E-11
7.67341E-12	5.05533E-12	1.85949E-12	2.71790E-09	1.51551E-09	8.45420E-10
5.67567E-10	3.88110E-10	2.93491E-10	2.15647E-10	1.40847E-10	1.01883E-10
7.04654E-11	5.19374E-11	3.51528E-11	2.96779E-11	3.83950E-11	1.32393E-11
7.15901E-12	4.05170E-12	1.46944E-12	1.51862E-09	8.18658E-10	4.83656E-10
3.19109E-10	2.28485E-10	1.64553E-10	1.11036E-10	7.84268E-11	5.28511E-11
4.02805E-11	2.90909E-11	2.54704E-11	3.14675E-11	9.93069E-12	6.09233E-12
3.71970E-12	1.67603E-12	8.44973E-10	4.47455E-10	2.54474E-10	1.76606E-10
1.32049E-10	8.67774E-11	6.15106E-11	4.25719E-11	3.10156E-11	2.27004E-11
1.77929E-11	2.34628E-11	9.03916E-12	4.54303E-12	2.77359E-12	1.24505E-12
5.23358E-10	2.69621E-10	1.48448E-10	9.75137E-11	6.62195E-11	4.57034E-11
3.08537E-11	2.43159E-11	1.70245E-11	1.39713E-11	2.00028E-11	7.10777E-12
3.99888E-12	2.18014E-12	9.71057E-13	3.17240E-10	1.45717E-10	7.54628E-11
4.99943E-11	3.54166E-11	2.29455E-11	1.82563E-11	1.26024E-11	1.08591E-11
1.55559E-11	5.53181E-12	3.11253E-12	1.69634E-12	7.50750E-13	1.87989E-10
7.80868E-11	3.98657E-11	2.68536E-11	1.81403E-11	1.38638E-11	9.57257E-12
8.84832E-12	1.18754E-11	4.22791E-12	2.38290E-12	1.54307E-12	5.72522E-13
9.84119E-11	3.95735E-11	2.15245E-11	1.36298E-11	1.06932E-11	7.95951E-12
6.80481E-12	9.27001E-12	3.33772E-12	1.91077E-12	1.11527E-12	4.13400E-13
6.89661E-11	2.38696E-11	1.13970E-11	9.52216E-12	7.66078E-12	7.70571E-12
9.97550E-12	3.47176E-12	1.90071E-12	1.22640E-12	4.67338E-13	3.82729E-11
1.26637E-11	7.22953E-12	5.42339E-12	5.43789E-12	6.93989E-12	2.38887E-12
1.28764E-12	7.96147E-13	3.46586E-13	3.84058E-11	6.64000E-12	3.55351E-12
2.79531E-12	3.51543E-12	1.19349E-12	6.29896E-13	4.26717E-13	1.37318E-13
1.52567E-11	3.46251E-12	3.01786E-12	3.71435E-12	1.36074E-12	7.20216E-13
4.21480E-13	1.52046E-13	1.51617E-11	2.56532E-12	3.28926E-12	1.19781E-12
6.98280E-13	3.34425E-13	1.45292E-13	2.10730E-11	4.10048E-12	1.37107E-12
7.08512E-13	4.70823E-13	1.64840E-13	5.82214E-11	2.01209E-12	1.00490E-12
6.26203E-13	1.43698E-13	9.69906E-12	3.41836E-13	2.53268E-13	1.08739E-13
4.27886E-12	8.63213E-14	7.13336E-14	3.77481E-12	3.38339E-14	2.72583E-12

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AUXILIARY FILE

GROUP AVERAGES OF N(E)

<N(E)> IS CONSTANT BETWEEN E¢I! AND E¢I+1!

ENERGY IN MEV

HEADER:
MAT MT
NR NP NBT INT

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9999 999
1 71 71 1

1.50000E-02	1.98062E-03	3.50000E-02	2.63889E-03	5.50000E-02	3.13381E-03
7.50000E-02	3.53802E-03	9.50000E-02	3.88029E-03	1.15000E-01	4.17766E-03
1.35000E-01	6.74949E-03	1.65000E-01	7.24725E-03	1.95000E-01	7.67303E-03
2.25000E-01	8.04112E-03	2.55000E-01	1.40897E-02	3.05000E-01	1.47925E-02
3.55000E-01	1.53520E-02	4.05000E-01	1.57946E-02	4.55000E-01	1.61377E-02
5.05000E-01	1.63900E-02	5.55000E-01	1.65871E-02	6.05000E-01	1.67204E-02
6.55000E-01	1.68015E-02	7.05000E-01	1.68366E-02	7.55000E-01	1.68306E-02
8.05000E-01	1.67926E-02	8.55000E-01	1.67245E-02	9.05000E-01	1.66266E-02
9.55000E-01	3.12447E-02	1.05000E+00	3.22818E-02	1.15000E+00	3.15311E-02
1.25000E+00	3.06779E-02	1.35000E+00	2.97545E-02	1.45000E+00	2.87687E-02
1.55000E+00	2.77453E-02	1.65000E+00	2.67069E-02	1.75000E+00	2.56436E-02
1.85000E+00	2.45877E-02	1.95000E+00	4.60312E-02	2.15000E+00	4.19516E-02
2.35000E+00	3.80788E-02	2.55000E+00	3.44450E-02	2.75000E+00	3.10439E-02

2.95000E+00	4.07321E-02	3.25000E+00	3.44394E-02	3.55000E+00	2.89632E-02
3.85000E+00	2.42289E-02	4.15000E+00	2.01906E-02	4.45000E+00	1.67740E-02
4.75000E+00	1.39047E-02	5.05000E+00	1.80473E-02	5.55000E+00	1.31090E-02
6.05000E+00	9.47973E-03	6.55000E+00	6.82923E-03	7.05000E+00	4.90397E-03
7.55000E+00	3.51503E-03	8.05000E+00	2.51890E-03	8.55000E+00	1.80529E-03
9.05000E+00	1.29354E-03	9.55000E+00	9.26071E-04	1.00500E+01	6.62143E-04
1.05500E+01	4.73301E-04	1.10500E+01	3.38290E-04	1.15500E+01	2.41660E-04
1.20500E+01	1.72452E-04	1.25500E+01	1.22917E-04	1.30500E+01	8.74626E-05
1.35500E+01	6.21394E-05	1.40500E+01	4.77709E-05	1.46000E+01	6.14927E-05
1.59000E+01	2.11848E-05	1.69000E+01	1.06383E-05	1.79000E+01	6.01237E-06
1.91000E+01	2.14551E-06	2.00000E+01	0.00000E+00		

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DOCUMENTATION

RELATIVE COVARIANCE MATRIX

GIVEN : ENERGY RANGE , ‹N(E)›, REL. STD. DEV.

AND CORRELATION MATRIX (*100)

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I	E¢I! MEV	E¢I+1! MEV	‹N(E)›	RSD %
1	0.015	0.035	1.98062E-3	10.35
2	0.035	0.055	2.63889E-3	4.68
3	0.055	0.075	3.13381E-3	4.28
4	0.075	0.095	3.53802E-3	4.78
5	0.095	0.115	3.88029E-3	3.41
6	0.115	0.135	4.17766E-3	3.34
7	0.135	0.165	6.74949E-3	2.65
8	0.165	0.195	7.24725E-3	2.24
9	0.195	0.225	7.67303E-3	2.25
10	0.225	0.255	8.04112E-3	1.85
11	0.255	0.305	1.40897E-2	1.84
12	0.305	0.355	1.47925E-2	1.69
13	0.355	0.405	1.53520E-2	1.73
14	0.405	0.455	1.57946E-2	1.66
15	0.455	0.505	1.61377E-2	1.65
16	0.505	0.555	1.63900E-2	1.80
17	0.555	0.605	1.65871E-2	1.75
18	0.605	0.655	1.67204E-2	1.62
19	0.655	0.705	1.68015E-2	1.82
20	0.705	0.755	1.68366E-2	1.87
21	0.755	0.805	1.68306E-2	1.83
22	0.805	0.855	1.67926E-2	1.75
23	0.855	0.905	1.67245E-2	1.93
24	0.905	0.955	1.66266E-2	1.74
25	0.955	1.050	3.12447E-2	1.56
26	1.050	1.150	3.22818E-2	1.22
27	1.150	1.250	3.15311E-2	1.21
28	1.250	1.350	3.06779E-2	1.24
29	1.350	1.450	2.97545E-2	1.24
30	1.450	1.550	2.87687E-2	1.23
31	1.550	1.650	2.77453E-2	1.23

32	1.650	1.750	2.67069E-2	1.25
33	1.750	1.850	2.56436E-2	1.20
34	1.850	1.950	2.45877E-2	1.23
35	1.950	2.150	4.60312E-2	1.15
36	2.150	2.350	4.19516E-2	1.14
37	2.350	2.550	3.80788E-2	1.14
38	2.550	2.750	3.44450E-2	1.22
39	2.750	2.950	3.10439E-2	1.19
40	2.950	3.250	4.07321E-2	1.17
41	3.250	3.550	3.44394E-2	1.19
42	3.550	3.850	2.89632E-2	1.18
43	3.850	4.150	2.42289E-2	1.19
44	4.150	4.450	2.01906E-2	1.32
45	4.450	4.750	1.67740E-2	1.37
46	4.750	5.050	1.39047E-2	1.35
47	5.050	5.550	1.80473E-2	1.50
48	5.550	6.050	1.31090E-2	1.47
49	6.050	6.550	9.47973E-3	1.58
50	6.550	7.050	6.82923E-3	1.65
51	7.050	7.550	4.90397E-3	1.79
52	7.550	8.050	3.51503E-3	1.86
53	8.050	8.550	2.51890E-3	2.07
54	8.550	9.050	1.80529E-3	2.16
55	9.050	9.550	1.29354E-3	2.25
56	9.550	10.050	9.26071E-4	2.47
57	10.050	10.550	6.62143E-4	2.69
58	10.550	11.050	4.73301E-4	2.90
59	11.050	11.550	3.38290E-4	2.93
60	11.550	12.050	2.41660E-4	3.44
61	12.050	12.550	1.72452E-4	3.59
62	12.550	13.050	1.22917E-4	5.04
63	13.050	13.550	8.74626E-5	4.47
64	13.550	14.050	6.21394E-5	6.27
65	14.050	14.600	4.77709E-5	9.61
66	14.600	15.900	6.14927E-5	12.41
67	15.900	16.900	2.11848E-5	14.70
68	16.900	17.900	1.06383E-5	19.44
69	17.900	19.100	6.01237E-6	32.31
70	19.100	20.000	2.14551E-6	76.95

100																			
7	100																		
8	35	100																	
9	25	30	100																
11	33	36	29	100															
8	22	24	22	33	100														
11	26	28	27	38	39	100													
14	33	36	35	46	45	55	100												
12	32	34	34	44	43	49	70	100											
9	20	21	21	27	31	36	50	48	100										
5	17	19	17	22	24	31	38	40	61	100									
7	18	18	17	23	24	30	39	40	66	67	100								
5	13	14	13	16	18	22	29	29	45	45	50	100							
3	9	9	9	11	14	20	26	25	40	42	47	47	100						
-1	-1	-2	0	1	3	6	6	7	21	23	26	31	36	100					
-0	0	1	-1	-0	4	6	4	10	26	24	30	33	36	35	100				
2	3	2	1	3	3	7	9	8	15	17	18	25	26	27	30	100			
1	1	-0	2	3	4	5	6	6	13	15	19	21	27	31	26	25	100		
1	2	5	5	6	6	9	9	7	10	13	13	18	18	21	19	20	21	100	
2	5	5	5	6	5	8	9	8	11	10	14	16	17	19	19	19	21	17	100

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13 15 100
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-13 -13 -16 -16 -7 39 35 39 37 36 35 32 35 36 100
-13 -28 -32 -27 -39 -36 -45 -52 -50 -44 -43 -43 -43 -37 -27 -27 -24 -23 -24 -23
-19 -18 -22 -20 -9 66 60 62 55 56 60 53 53 55 38 100
-13 -30 -32 -30 -37 -36 -45 -52 -48 -44 -43 -43 -43 -37 -27 -27 -25 -23 -25 -23
-19 -18 -22 -23 -9 61 60 62 55 60 60 53 58 55 38 16 100
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-13 -15 -12 -13 -15 -9 -7 -9 -9 -8 -10 -7 -8 -8 -4 -1 -1 100
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-19 -19 -18 -20 -25 -18 -13 -14 -14 -17 -11 -12 -14 -13 -9 -1 -1 47 55 100
-3 -4 -5 -9 -5 -7 -9 -10 -11 -14 -16 -18 -14 -16 -16 -15 -15 -17 -15 -14
-15 -17 -14 -16 -22 -28 -22 -22 -19 -22 -21 -18 -16 -15 -16 -9 -9 25 34 65
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-3 -4 -5 -10 -7 -7 -9 -10 -11 -14 -14 -18 -17 -16 -19 -16 -16 -17 -17 -17
-18 -15 -16 -15 -22 -25 -23 -23 -17 -20 -22 -19 -16 -16 -17 -14 -10 25 34 58
72 100
-3 -0 -2 -6 -1 -3 -4 -5 -5 -12 -14 -16 -15 -15 -18 -16 -16 -17 -13 -12
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50 62 100
0 4 5 -1 4 2 4 5 3 -6 -7 -9 -7 -11 -13 -11 -12 -12 -10 -8
-9 -8 -6 -7 -13 -30 -27 -28 -25 -23 -28 -24 -20 -25 -25 -32 -32 9 16 24
33 40 66 100
1 6 5 1 7 5 6 7 6 -3 -4 -7 -7 -9 -11 -10 -9 -10 -5 -5
-8 -7 -5 -4 -10 -31 -26 -28 -26 -22 -25 -26 -21 -22 -28 -36 -37 6 14 17
27 31 51 75 100
1 6 8 4 8 6 9 9 8 -2 -5 -6 -4 -5 -9 -11 -10 -10 -6 -6
-6 -7 -5 -2 -8 -34 -31 -32 -28 -24 -27 -29 -21 -21 -32 -39 -36 4 12 14
21 32 38 56 75 100
2 9 10 7 11 10 11 12 13 2 2 -0 -0 -4 -9 -6 -7 -6 -2 -2

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-5 -4 -1 -0 -6 -33 -32 -32 -25 -26 -29 -26 -25 -23 -31 -40 -40 2 10 4
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2 9 10 8 12 9 12 12 12 2 0 -0 -0 -4 -9 -6 -7 -5 -2 -3
-5 -4 -2 1 -6 -33 -30 -30 -25 -26 -29 -29 -23 -24 -31 -40 -40 0 8 7
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-3 -4 -1 1 -4 -31 -28 -28 -23 -27 -27 -27 -21 -22 -30 -41 -39 -1 6 3
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3 10 11 10 15 13 15 15 16 6 6 2 3 -1 -5 -4 -3 -4 -0 -0
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4 11 12 10 14 13 16 18 17 7 7 4 6 0 -4 -2 -2 -1 0 1
-0 -1 2 3 -2 -30 -27 -30 -21 -22 -24 -24 -17 -18 -31 -45 -43 -2 5 -1
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4 12 13 10 15 13 16 18 18 8 7 6 6 3 -3 -0 2 -2 0 3
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4 11 12 10 16 12 17 19 17 9 10 6 6 4 1 1 2 1 3 4
2 1 4 4 -1 -28 -25 -29 -19 -20 -22 -23 -15 -16 -32 -46 -42 -4 3 -2
10 13 23 32 36 43 45 46 47 51 53 63 75 100
4 11 12 9 15 12 16 18 17 8 9 8 7 4 -0 2 3 1 3 4
2 1 3 4 1 -27 -25 -27 -19 -20 -20 -22 -17 -16 -31 -45 -43 -5 3 -2
10 13 23 32 36 42 44 46 45 49 51 56 56 72 100
3 11 12 10 14 12 16 18 18 9 8 8 7 4 1 1 2 1 4 5
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8 11 19 28 31 38 41 41 41 44 45 49 48 54 67 100
3 11 12 10 13 12 15 18 17 9 9 8 8 5 0 2 2 3 4 4
3 2 5 5 1 -23 -19 -23 -14 -17 -17 -18 -12 -13 -26 -41 -39 -4 0 -4
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7 8 13 20 21 26 29 28 28 32 32 35 33 34 36 35 34 35 48 100
2 8 9 7 10 9 10 12 11 7 7 5 5 3 1 2 3 1 3 4
2 2 3 4 1 -16 -14 -15 -10 -10 -12 -13 -9 -8 -21 -33 -33 -3 1 -3
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1 5 6 5 8 6 8 9 9 6 4 4 4 3 1 2 1 1 2 2
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30 27 100
1 4 4 4 6 5 6 7 6 3 3 3 3 1 1 0 2 1 2 2
1 1 1 3 0 -8 -7 -9 -5 -6 -7 -8 -4 -4 -11 -20 -17 -2 2 -1
2 6 6 10 12 10 15 15 17 17 18 19 17 19 20 19 18 18 21 24
23 15 23 100
1 2 2 3 3 2 4 4 4 3 3 2 2 1 0 1 1 0 1 1
1 0 1 1 -0 -6 -6 -7 -4 -3 -4 -4 -3 -3 -8 -13 -11 -2 -0 -1
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   2   3   5   7   8  11  10  10  11  11  11  12  12  14  13  13  13  14  15  20
  19  10  17  14 100
   1   2   2   2   2   2   2   3   3   2   1   1   1   1  -0   0   0  -0   0   1
   0  -0   1   1  -1  -5  -5  -5  -4  -2  -3  -3  -2  -2  -6  -7 -10  -1   2  -2
   2   2   5   6   7   7   8   8   8   9   9  10  10  11  11  11  11  11  12  16
  15   7  12  11  12 100
   0   1   2   1   2   1   2   3   3   1   1   2   1   1  -0   0   0   0   1   1
   0   0   1   1  -0  -4  -3  -4  -2  -3  -3  -3  -3  -3  -6  -7  -7   0   1  -0
   1   3   2   4   5   5   6   6   7   8   8   8   8   8  10  10  10  10  11  13
  12   6  11  10  10   8 100
   0   1   1   1   1   1   1   2   2   1   1   1   1   0  -1  -0  -0  -1  -0   0
  -0  -0   0   0   1  -3  -3  -3  -2  -2  -3  -3  -2  -2  -3  -5  -5   0   1  -0
   3   1   3   4   4   5   5   5   5   7   6   6   7   8   8   8   8   8   9  11
  10   5   9   9   7   6   5 100
   0   1   1   1   1   1   1   1   1   1   1   1   1   1   0   0   0   0   0   1
   0   0   1   1   1  -2  -2  -2  -2  -2  -2  -2  -2  -2  -3  -3  -3  -1  -1   0
   1   1   1   2   2   4   4   4   4   4   4   4   4   5   5   5   5   6   6   8
   7   4   6   4   5   4   4   2 100
   0   0   0   0   1   0   1   1   1   0   0   0   0   0  -0  -0  -0  -0  -0  -0
  -0  -0   0   0  -0  -1  -1  -1  -1  -1  -1  -1  -1  -1  -2  -3  -0   1   1   1
   1   1   1   1   2   2   2   2   2   2   2   2   2   3   3   3   3   3   3   3
   3   1   2   2   2   1   2   2   1 100
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From a paper presented by W. Mannhart at the 6th ASTM Symposium on Reactor Dosimetry, 31 May - 5 June 1987, Jackson Hole, WY, USA.

Table 2 Cf-252 spectrum-averaged neutron cross sections (in millibarn)

REACTION	CALCULATION**		EXPERIMENT	RSD	C/E
F-19(N,2N)	1.714E-2*	[31]	1.613E-2	3.40	1.063
MG-24(N,P)	2.101E+0	[32]	1.998E+0	2.42	1.052
AL-27(N,P)	5.027E+0		4.885E+0	2.14	1.029
AL-27(N,A)	1.034E+0		1.017E+0	1.47	1.017
	9.886E-1	[33]			0.972
S-32(N,P)	7.591E+1		7.262E+1	3.50	1.045
TI-46(N,P)	1.317E+1		1.409E+1	1.76	0.935
TI-47(N,P)	1.933E+1	[34]	1.929E+1	1.66	1.002
	2.406E+1				1.247
TI-48(N,P)	4.002E-1		4.251E-1	1.89	0.941
V-51(N,P)	6.638E-1	[35]	6.493E-1	1.95	1.022
V-51(N,A)	3.878E-2	[36]	3.904E-2	2.22	0.993
MN-55(N,2N)	4.623E-1		4.079E-1	2.34	1.133
FE-54(N,P)	8.790E+1		8.692E+1	1.34	1.011
FE-56(N,P)	1.374E+0		1.466E+0	1.77	0.937
NI-58(N,P)	1.134E+2		1.176E+2	1.30	0.964
NI-58(N,2N)	9.048E-3	[37]	8.961E-3	3.59	1.010
	8.103E-3				0.904
CO-59(N,P)	1.699E+0	[38]	1.692E+0	2.49	1.004
CO-59(N,A)	2.110E-1		2.220E-1	1.86	0.950
CO-59(N,2N)	4.266E-1		4.055E-1	2.52	1.052
CU-63(N,G)	9.673E+0		1.045E+1	3.24	0.926
CU-63(N,A)	6.581E-1	[39]	6.893E-1	1.98	0.955
	7.383E-1				1.071
CU-63(N,2N)	2.082E-1	[32]	1.845E-1	3.98	1.128
CU-65(N,2N)	6.766E-1		6.587E-1	2.24	1.027
ZN-64(N,P)	3.913E+1	[32]	4.063E+1	1.64	0.963
ZR-90(N,2N)	2.196E-1	[32]	2.212E-1	2.90	0.993
IN-115(N,G)	1.217E+2		1.257E+2	2.23	0.968
IN-115(N,N')	1.834E+2		1.976E+2	1.37	0.928
I-127(N,2N)	2.349E+0		2.071E+0	2.75	1.134
AU-197(N,G)	7.619E+1		7.686E+1	1.59	0.991
AU-197(N,2N)	5.648E+0		5.511E+0	1.83	1.025
U-235(N,F)	1.237E+3		1.210E+3	1.20	1.022
NP-237(N,F)	1.360E+3		1.361E+3	1.58	0.999
U-238(N,F)	3.158E+2		3.257E+2	1.63	0.970
PU-239(N,F)	1.794E+3		1.812E+3	1.37	0.990

RSD: RELATIVE STANDARD DEVIATION IN %

* Read as 1.714×10^{-2}

** Calculated with the evaluated neutron spectrum and cross-section data from either ENDF/B-5 or the quoted references.

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[35] Smith, D.L., Meadows, J.W., Kanno, I., "Measurement of the V-51(n,p) reaction cross section from threshold to 9.3 MeV by the activation method", Argonne National Laboratory, Ill., Rep. ANL/NDM-85 (June 1984)

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