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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

UPDATE TO NUCLEAR DATA STANDARDS FOR NUCLEAR MEASUREMENTS

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Summary Report of a Consultants' Meeting held in Vienna, Austria,
2 to 6 December 1996

Edited by H. Wienke
Nuclear Data Section
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Contents

Preface

The following document is an update of the 1991 NEANDC/INDC Nuclear Standards File [INDC(SEC)-101] to indicate the status and extension of cross section standards for the $^{10}B(n,\alpha)$ reaction in the energy region below 20 MeV; and the H(n,n), $^{235}U(n,f)$, $^{238}U(n,f)$, and $^{209}Bi(n,f)$ reactions for selected energy regions above 20 MeV. The work on the $^{10}B(n,\alpha)$ reaction was motivated by the need to improve the database for this standard which has many discrepant data sets and to extend the energy range over which it can be used as a standard. For the other reactions new data have been measured which motivate a review of these cross sections. Since the 1991 publication, there has been considerable interest in standards for neutron energies above 20 MeV neutron energy. Efforts to provide the standards at these higher energies were the focus of activities by the INDC Standards Subcommittee, under the chairmanship of Henri Condé. This work led to a specialists meeting on neutron cross section standards for the energy region above 20 MeV which was held in Uppsala, Sweden in 1991 which provided the foundation for the present update. In this report there are extensions in energy above 20 MeV to the existing ^{235}U and ^{238}U fission cross section standards. Also it has been recommended that the ^{209}Bi fission cross section be included as a new standard for the energy region above 20 MeV. This cross section which has a large effective threshold (above 20 MeV) is especially useful for high neutron energy dosimetry applications.

For the n-p and $^{10}B(n,\alpha)$ cross sections, the status of the standards and recommendations for improving them are given. For the fission standards, numerical tabulations are also given. The standards data sets which are available can be accessed via ftp using the address, iaeand.iaea.or.at and the username, standards. All uncertainties shown in this report are standard deviations.

The objective of this publication is to provide concise and readily usable reference guidelines for essential nuclear standards quantities for a variety of basic and applied endeavors.

Introduction

The majority of basic and applied nuclear data measurements are made relative to reference standards. It is essential that these standards be well defined, clearly referenceable and easily available. This update to the INDC/NEANDC nuclear standards file provides such standard-reference quantities in a manner not otherwise available.

In order to improve the accuracy and consistency of experimental results it is recommended

- that standards tabulated in this report be adopted for all measurements, and
- that when converting relative measured values to cross section values the numerical values given herein be employed.

These recommendation will facilitate future evaluation work and ease later renormalizations when improved standard-reference information becomes available.

The narrative summaries consist of concise and up-to-date statements delineating nuclear reference standards judged of importance. These statements were prepared by selected specialists who outlined the contemporary status (including shortcomings) and suggested possible avenues toward improvement. The statements explicitly support the accompanying numerical tabulations and set forth other important nuclear standards not amenable to straightforward numerical tabulation.

The H(n,n) Cross Section in the 20 MeV to 350 MeV Range

Introduction

Absolute measurements of neutron-induced cross sections are difficult to perform, since the absolute fluence of a neutron beam cannot easily be measured. This is contrary to charged particle-induced reactions where, e.g., the proton beam intensity can be determined by measuring the beam current. On the other hand, the neutron total cross section can be determined to high accuracy (better than 1 %) by a measurement of the sample-in to sample-out ratio, without knowledge of the absolute beam intensity. Such a simply measured cross section does not exist for protons.

For hydrogen, the differential elastic scattering cross section can be directly related to the total cross section, since no other channels of importance are open below the pion production threshold at about 280 MeV (the capture and Bremsstrahlung cross sections are very small). The pion production channel can be neglected up to about 350 MeV, at which it contributes only 0.5 % to the total cross section. The total cross section is known from several measurements (e.g., refs. [1,2]) to within 1 % for the energy region considered here.

The differential H(n,n) cross section has been used as a standard relative to which other neutron emission cross sections, e.g., elastic or inelastic scattering, have been measured in the several MeV region. It has furthermore been used as a standard for neutron fluence measurements, most often by detection of the recoil proton with a telescope detector. The first case corresponds to detection of the scattered neutron at small angles, while the latter is associated with large angle scattering in the center-of-mass system. Thus, a good knowledge of the angular distribution in both hemispheres is desired for this reaction. Since the most important use of this cross section is for neutron fluence measurements, precision data at the backward angles are especially required.

The H(n,n) standard

In 1991 the differential H(n,n) cross section was for the first time accepted by the NEANDC/INDC as a primary standard for cross section measurements in the 20 MeV to 350 MeV range [3]. To that end the VL40 phase-shift solution of Arndt *et al.*, at Virginia Polytechnic Institute and State University (VPI&SU) was adopted as the best source for numerical values [4]. VL40 is an energy-dependent partial-wave representation of combined (pp + np) elastic scattering data below 400 MeV. Above 350 MeV it was, however, felt that the inelastic cross section is no longer negligible. VL40 was determined by fitting a number of parameters to the existing pp and np database of about 2000 and 3000 data points, respectively. No uncertainties are given for the VL40 cross sections, but in ref. [3] they were+ estimated to rise from a level of around 1 % at energies below 50 MeV to a "few" percent at higher energies.

The cross sections obtained from the VL40 solution can be accessed through the Scattering Analysis Interactive Dial-in system (SAID) at VPI&SU through telnet: vtinte.phys.vt.edu with login PHYSICS and password QUANTUM. A users guide can be found via WWW on http://nn-online.phys.vt.edu/~CAPS/

New data and recently discovered problems

Since 1991 new precision data at 96 and 162 MeV have come from the Svedberg Laboratory in Uppsala [5,6]. These data tend to be steeper than previous data in the very backward direction, i.e., 150° to 180°, and prompted the Uppsala group to perform a detailed study of the world H(n,n) database [7]. It was then discovered that there were severe discrepancies between data sets, both with respect to the shape of the angular distributions and to the normalization of the data.

The existing data seem to fall into two main "families" with respect to the angular shape. The first one is dominated by the Bonner data [8], which have a flattish angular distribution at backward angles. The second one, which includes the data from Uppsala, as well as the Hürster data from Paul-Scherrer-Institute [9], have a steeper angular shape. Unfortunately, the Hürster data are missing in Arndt's database, and thus the backward cross section is mainly determined by the Bonner data. Another problem is that if the Bonner data contain a systematic error, it would affect the entire result since the large amount of data give a high weight and correlations are not taken into account in the Arndt procedure. It is not possible today to judge which family, if any, is the correct one, and therefore these findings should not lead to a change of the existing standard. However, attention has to be paid to the fact that the uncertainties might be larger than previously assumed, especially close to 180°.

The discovered discrepancies are illustrated in figures 1, 2, and 3 which show the differential H(n,n) cross section at around 100, 160 and 320 MeV. As can be seen, the two families of data diverge more and more when approaching 180°.

The direct relation between the total cross section and the differential scattering cross section mentioned above requires, however, that the full angular distribution be measured. This is realistically not the case. In fact most data are taken in the backward hemisphere, i.e., 120° to 180°, by detection of the energetic recoil proton. Therefore, most data below 300 MeV are given as relative cross sections only. Above 300 MeV the simultaneously measured reaction $n + p \rightarrow d + \pi^0$ is most often used for normalization. Since this reaction is as difficult to measure as the np scattering, cross sections are derived from the isospin-related $p + p \rightarrow d + \pi^+$ reaction by correcting for Coulomb effects and multiplying by a factor of 0.5 to take the assumption of isospin invariance into account. This cross section has, however, undergone dramatic changes over the years. Also if only the most recent data (after 1975) are considered, the spread is of the order of ±10 %, which probably reflects the uncertainty that should be assigned to the average of these data. In addition, the methods used to convert the $p + p \rightarrow d + \pi^+$ cross section to that of the corresponding n + p reaction is only correct to first order. Niskanen and Vestama [10] have recently estimated the magnitude of isospin symmetry breaking effects for this case. They find that at 300 MeV, i.e., just above the threshold, the higher order correction is about +10 %, whereafter it falls to about -3 % at 500 MeV, and then rises rapidly up to about +7 % at 600 MeV.

The conclusion from this is that for most angular distribution data no normalization is given below 300 MeV, and above that it is uncertain to the 10 % to 15 % level. As a consequence, Arndt in his analysis uses a floating normalization for all differential data, which instead are normalized to his phase-shift solution. At an early stage this solution was, however, affected by the uncertain normalization of the data, although it is an average over many data sets. The normalization is performed by a χ^2 minimization procedure, which in case of large shape discrepancies could lead to inconsistencies between the differential data and the total cross section, since the solid angle element vanishes at 0° and 180°. Therefore, it seems urgent that a few measurements be performed to high precision on an absolute scale, which means either that most of the angular distribution has to be covered for a reliable normalization to the total cross section, or the data have to be measured with a tagged neutron beam. The first method has been chosen by the Uppsala group by extending the previous data at 96 MeV and 162 MeV down to about 70°, which gives a normalization uncertainty at the two energies of about 1.5 % and 2.3 %, respectively [11,12]. The second method is being used in a precision study at the Indiana University Cyclotron Facility [13], where the backward-angle cross section will be measured at 190 MeV using a tagged neutron beam produced at the cooler ring.

Conclusions and recommendations

In spite of all the difficulties and inconsistencies discovered in the H(n,n) database, we recommend that the VL40 results continue to serve as the primary cross section standard in the energy range 20 MeV to 350 MeV. There is no firm basis for changing the standard until most of the questions raised have been resolved. In addition, more recent phase-shift solutions from Arndt give similar cross sections to those of the VL40 results, since not much new data have been added after 1991.

One should, however, assign to this standard somewhat larger uncertainties than previously assumed. To our judgement, the uncertainties could be as large as ±10 % close to 180° in the energy region above 100 MeV, which essentially corresponds to the deviations between the different data sets. Considering these large discrepancies between the data close to 180°, it might be more favorable to use the cross section at 150° instead. Here the data do not differ so much, and a recoil detector can easily be positioned at an angle of 15° in the laboratory system. Below 100 MeV the database is scarce, especially in the backward hemisphere. Therefore more data are needed, both to improve future phase-shift solutions and to give a better possibility for estimating the uncertainties.

Moreover, since no judgement of the quality of the experimental data is made in Arndt's procedure, he should be encouraged to include also the published data above 200 MeV from PSI in the backward hemisphere [9]. As soon as the more recent and more extensive additional data set from PSI is released [14], this should also be included. The recent measurement now under analysis by Ullmann [15] of the ratio of the 170° and 140° cross sections should also be taken into account.

To facilitate the use of VL40 as a standard for the community, pointwise data in 5° steps from 20 MeV to 350 MeV are included in the IAEA/NDS standards file. This file can be accessed via ftp using the address, iaeand.iaea.or.at and the username, standards.

Concern was expressed regarding a cross section standard at energies higher than 350 MeV, which are of importance for some upcoming applications. Arndt has other phase-shift solutions that extend up to over 1 GeV, but the problem is that there are updates made four times a year, with slight changes in the cross section as a result. It is therefore important that experimentalists using the H(n,n) cross section for normalization at high energies numerically give the value of the reference used, for possible later adjustment. A solution to this problem might be to use the JENDL High Energy File, which is available in ENDF/B-VI format and is well documented [16].

Finally, we would like to encourage experimentalists to perform more precision measurements of this cross section, which is so important from a fundamental point of view, as well as for many applications. We here point out the excellent opportunities that would open up if the planned 1.5 GeV proton linac of the Neutron Science Research Center at JAERI is built. With dedicated experimental equipment, this facility would be capable of giving answers to the open questions.

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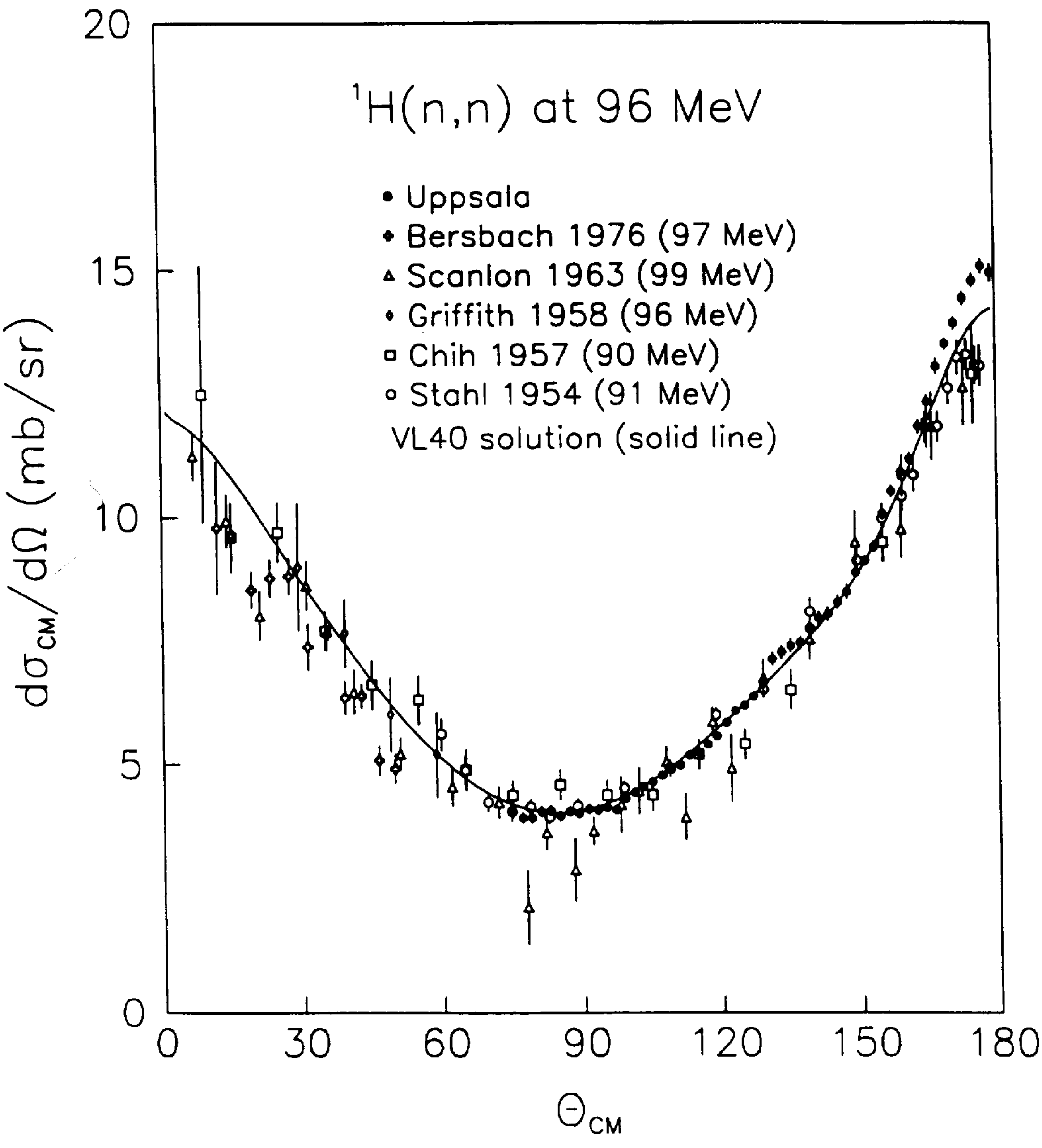

Fig. 1 Measurements of the differential H(n,n) cross section near 100 MeV compared with the VL40 solution of Arndt [3].

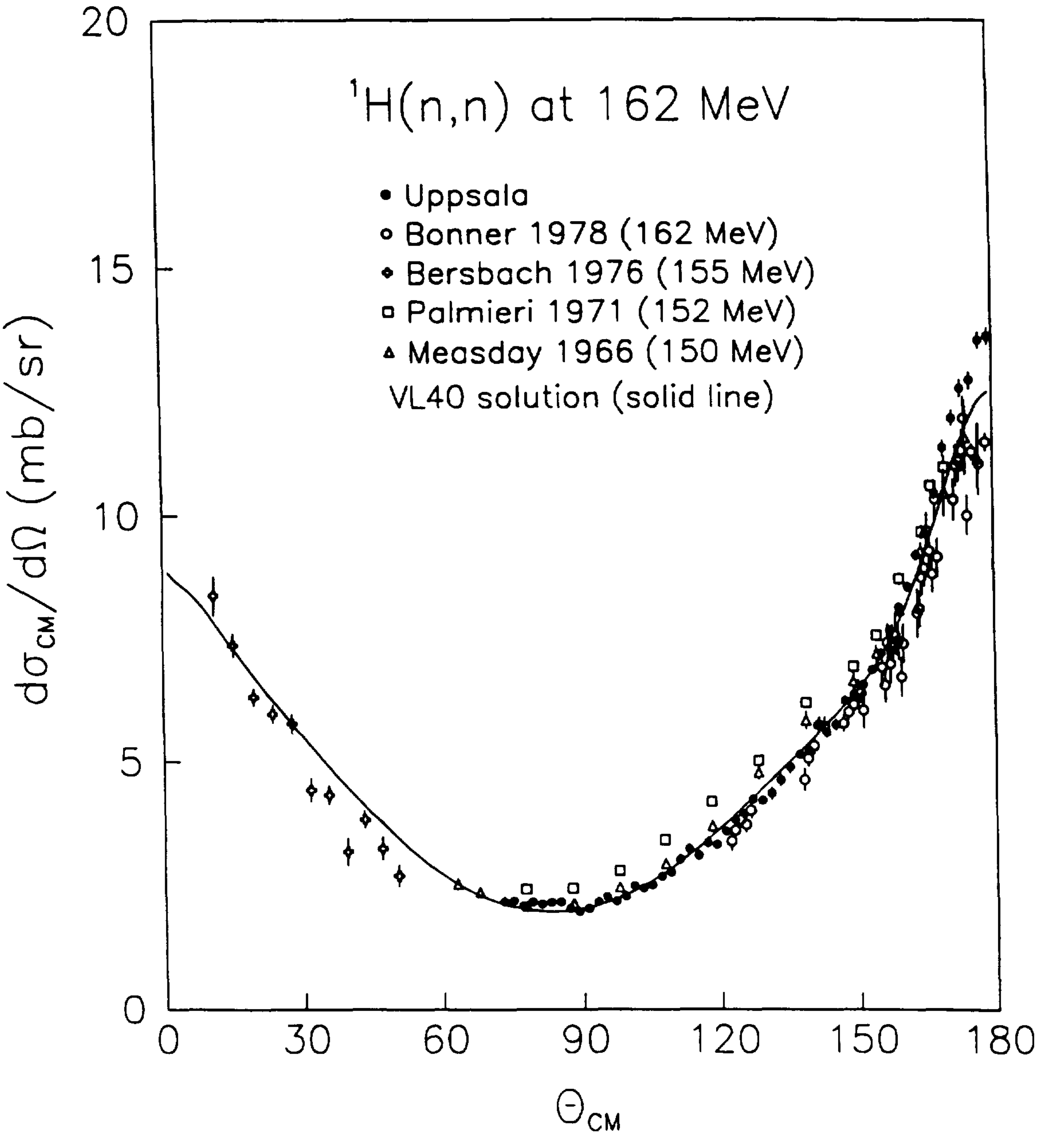

Fig. 2 Measurements of the differential H(n,n) cross section near 160 MeV compared with the VL40 solution of Arndt [3].

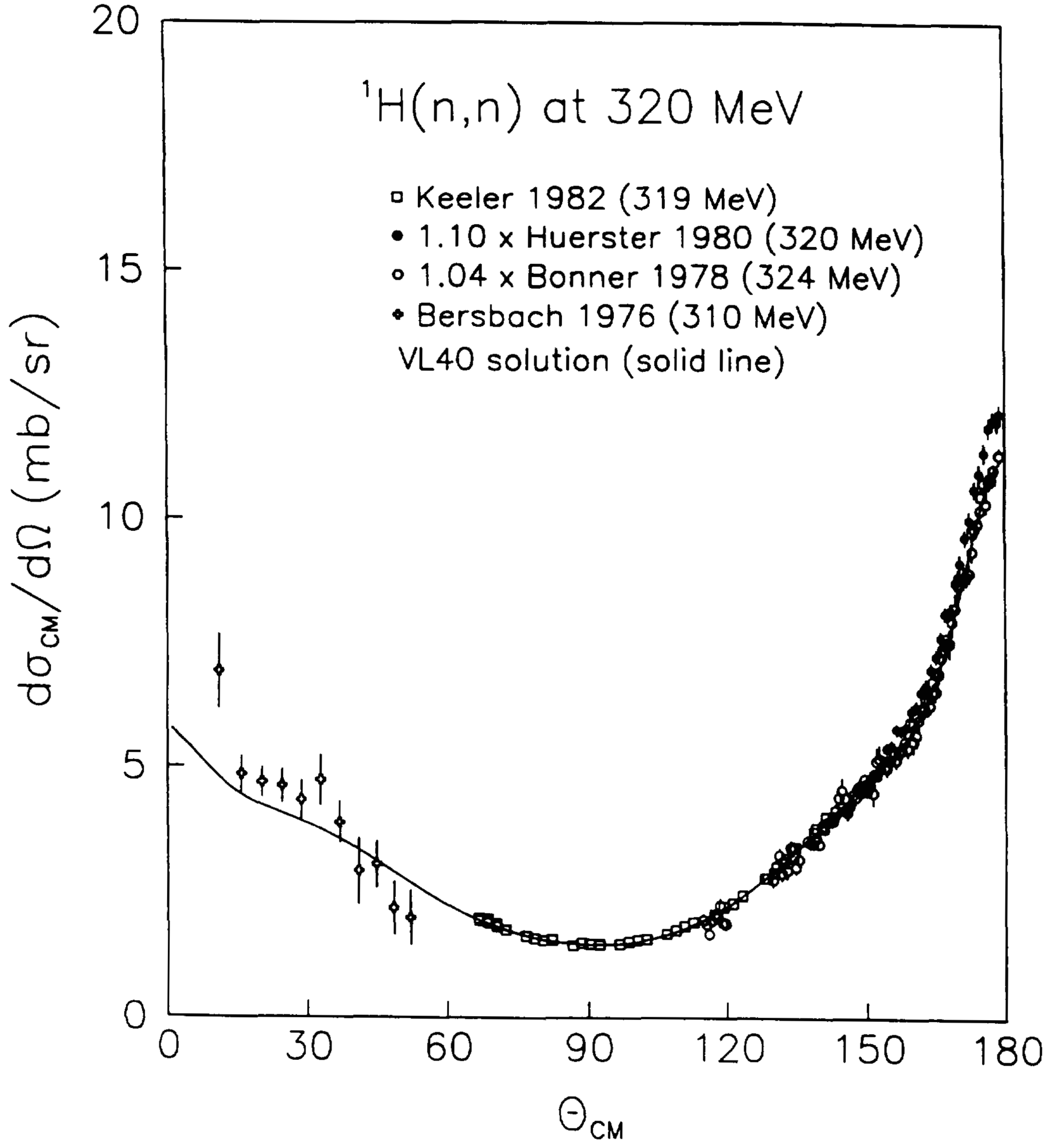

Fig. 3 Measurements of the differential H(n,n) cross section near 320 MeV compared with the VL40 solution of Arndt [3].

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The $^{10}B(n,\alpha)^{7}Li$ Cross Section

The recommended reference data for $^{10}B(n,\alpha)$ in the 1991 Nuclear Standards File are actually the ENDF/B-VI evaluated cross section data. The main concern expressed in the $^{10}B(n,\alpha)$ summary of that document was the small uncertainties of the evaluated data file [1]. Furthermore, there are indications [2] from an analysis of spectrum integrated cross sections from benchmark fast reactor neutron fields that this cross section should be increased in the energy region above 50 keV relative to the ENDF evaluation.

The $^{10}B(n,\alpha)$ standards have received considerable attention as a result of their relatively poor database and the problems they caused in the ENDF/B-VI standards evaluation process. An interlaboratory collaboration, which later became a subgroup of the Working Party on International Nuclear Data Measurement Activities, of the Nuclear Energy Agency Nuclear Science Committee was formed to provide a mechanism for improving these cross sections. Working groups or task forces such as these have been very successful in the past at resolving data problems. The $^{10}B(n,\alpha)$ subgroup has representatives from the measurement, evaluation and user communities. Its objective is to have several laboratories collaborate on programs to improve the database relevant to an evaluation of the $^{10}B(n,\alpha)$ standard cross sections. There has been an appreciable effort at a number of major laboratories located in the USA and Europe on the $^{10}B(n,\alpha)$ cross section problem since the formation of this subgroup. Work has been done on the branching ratio, the $^{10}B(n,\alpha_1\gamma)$ cross section, the total neutron cross section, the differential cross section for the $^{10}B(n,\alpha)^{7}Li$ reaction, and the $^{10}Be(p,n)$ reaction. These measurements can be effectively utilized in helping to define the $^{10}B(n,\alpha)$ cross sections when used in an R-matrix analysis. Such an analysis can use neutron total, scattering and reaction cross sections for ^{10}B; as well as additional measurements such as angular distributions, polarization and charged-particle studies involving the ^{11}B compound nucleus to define the parameters needed to accurately calculate the $^{10}B(n,\alpha)$ cross sections.

***Status of Recent and Ongoing Measurements*:**

Branching Ratio Measurements

Measurements of the ^{10}B branching ratio, the ratio of the $^{10}B(n,\alpha_0)$ to the $^{10}B(n,\alpha_1)$ cross sections, provide direct information on the ratios of the $^{10}B(n,\alpha)$ cross section standards. Weston and Todd [3] measured the branching ratio from 20 keV to 1000 keV neutron energy at the ORNL LINAC (ORELA) facility. In figure 1, these data are compared with the ENDF/B-VI evaluation. The measurements are 10 % to 30 % low in the 100 keV to 600 keV energy region compared with the ratios calculated from the ENDF/B-VI cross sections. The data agree with ENDF/B-VI at the lowest and highest energies of the experiment. The error bars represent one standard deviation total uncertainties. In view of the large differences observed in ref. [3], new branching ratio measurements are planned at IRMM by Hambsch using a Frisch gridded ionization chamber. Such measurements also offer the possibility of getting information concerning the angular distribution.

$^{10}B(n,\alpha_1\gamma)$ Measurements

In a NIST/ORNL collaboration, measurements [4] were made at the ORELA facility of the shape of the $^{10}B(n,\alpha_1\gamma)$ cross section from 0.3 MeV to 4.0 MeV neutron energy. The cross sections which were obtained, normalized to the ENDF/B-VI evaluation over the region from 0.2 MeV to 1 MeV, agree with the ENDF/B-VI evaluation below 1.5 MeV. However, above 1.5 MeV they differ as much as 40 % from the ENDF/B-VI evaluation. The interest in extending the $^{10}B(n,\alpha_1\gamma)$ standard to higher neutron energies and confirming the results obtained at the ORELA facility led to a NIST/LANL collaborative measurement [5] at the WNR facility at LANL. The data cover the range from 300 keV to 20 MeV. Preliminary results compared with the ORELA data and the ENDF/B-VI evaluation are shown in figure 2. The agreement with the ORELA experiment above 1 MeV confirms the discrepancy with ENDF/B-VI in the energy region above 1.5 MeV. In this figure, the experimental data were normalized to the ENDF/B-VI evaluation for the energy region below 1 MeV to facilitate comparison of the measurements and evaluation.

An additional measurement [6] made by this same collaboration at the ORELA facility extended the cross section to lower energies so that better normalization of shape measurements could be made. The measurement covered the neutron energy range from 10 keV to 1 MeV. The preliminary results normalized to the ENDF/B-VI evaluation over the region from 10 keV to 20 keV are shown in figure 3. These data are lower than the ENDF/B-VI shape by about 5 % in the region above 100 keV. A number of other experiments listed in ref. [5] show a similar result. Using the normalization established from the measurements would require that the Schrack data in figure 2 be reduced by 5 %.

Total Cross Section Work

Many earlier measurements of the ^{10}B total neutron cross section have been affected by the quality of the transmission samples being used and difficulties with backgrounds. Three new measurements have been made of this cross section with special concerns about the quality of the samples and evaluation of backgrounds in an effort to improve the $^{10}B(n,\alpha)$ standards. Brusegan *et al.* [7] have reported preliminary measurements of the ^{10}B total cross section made at the IRMM LINAC (GELINA) facility. Data were presented for the energy region from 80 eV to about 100 keV. The ^{10}B results agree with the ENDF/B-VI evaluation below 10 keV to within half a percent, but are high by up to 7 % in the energy range from 10 keV to 100 keV. Additional data are under analysis which will improve the present results and extend them to higher energies. Also presented in ref. [7] are preliminary measurements made of the ^{10}B total cross section at the IRMM 7 MV Van de Graaff facility by Crametz and Wattecamps [8]. The measurements were made using a white source over the energy region from 1.5 MeV to 18 MeV. The ^{10}B results agree with ENDF/B-VI at the higher energies within the uncertainties. The data are slightly low at the lowest energies compared with ENDF/B-VI. Further work is in progress with monoenergetic neutrons in the energy range from 0.2 MeV to 2 MeV at this facility.

Measurements were also made by Wasson *et al.* [9] at ORELA of the ^{10}B total cross section. The neutron energy region covered by this work extended from 20 keV to 20 MeV. The ^{10}B total cross section measurements agree with the ENDF/B-VI evaluation for neutron energies greater than about 2 MeV, but are lower by as much as about 4 % between 600 keV and 2 MeV and are greater by as much as about 5 % below 600 keV. A comparison of the three new ^{10}B total cross section measurements is shown in figure 4. There is generally good agreement among these measurements within the uncertainties.

Angular Distribution Measurements

Measurements have been made by Haight of the angular distribution of α particles from the ^{10}B(n,α) reaction at the WNR facility at LANL [10]. Data for this experiment were obtained for the energy range from about 1 MeV to 6 MeV. The angular distribution was measured at laboratory angles of 30°, 60°, 90°, and 135° using a thin (3800 Å) ^{10}B film as a target. For this experiment, the α groups are not resolved so the angular distribution includes the contribution from both of the groups. The data from this experiment are now undergoing analysis. Further work has recently been done to reduce the backgrounds for this experiment. This is allowing the experiment to be repeated using only the energy detector so that data can be obtained to lower charged- particle energy. It may even be possible to obtain useful data on the ^{7}Li angular distribution. New measurements are also being made with an ionization chamber containing a ^{10}B deposit.

Charged-Particle Data

Measurements have begun by Massey at Ohio University of the ^{10}Be(p,n) reaction [11]. The data that have been obtained are excitation functions at 0° in the laboratory system for proton energies from 1.5 MeV to 4.0 MeV. Full angular distributions are expected in further work. The results of this work will provide data in the region of interest for the R-matrix analysis of the ^{11}B system.

Summary

Though many of the experiments are preliminary, the lower ^{10}B(n,$\alpha_1\gamma$) cross section, the lower branching ratio and the higher total cross section indicate a discrepancy in the hundred keV energy region in one or more of the measurements reported here.

Changes in the evaluated ^{10}B(n,α) cross sections resulting from the measurements made since the ENDF/B-VI evaluation will be estimated. The impact on the ^{10}B(n,α) standard will be estimated from R-matrix analyses by Gerry Hale, the ENDF/B-VI evaluator for this cross section, using the above mentioned data sets which should be finalized by the middle of 1997 by the subgroup working to improve this cross section.

The ENDF/B-VI evaluation was performed by a comprehensive process which involved R-matrix evaluations for ^{11}B and ^{7}Li which were combined with the results of a simultaneous evaluation. The database for the ^{11}B and ^{7}Li measurements were divided between the two evaluation techniques. It will not be possible to do a complete evaluation in this manner for this investigation. Instead, the relative change resulting from the recent measurements will be determined by comparing two R-matrix evaluations; one using the entire ^{10}B database used in the ENDF/B-VI evaluation and a second using that database plus the recent measurements. Recently point-wise evaluations of the $^{10}B(n,\alpha)$ cross section and the ^{10}B total cross section were done by Kafala [12] using the neutron database only. The $^{10}B(n,\alpha_1\gamma)$ cross section was not evaluated. These evaluations included the most recent data however they are somewhat limited in that neither R-matrix nor simultaneous evaluation techniques were employed. For the total cross section, the most recent measurements [7-9] have been weighted heavily in this evaluation so the changes compared with ENDF/B-VI are generally consistent with that expected based on figure 4. There are also significant differences compared with the ENDF/B-VI evaluation for the $^{10}B(n,\alpha)$ standard cross section.

New recommendations for the ^{10}B standard cross section are forthcoming.

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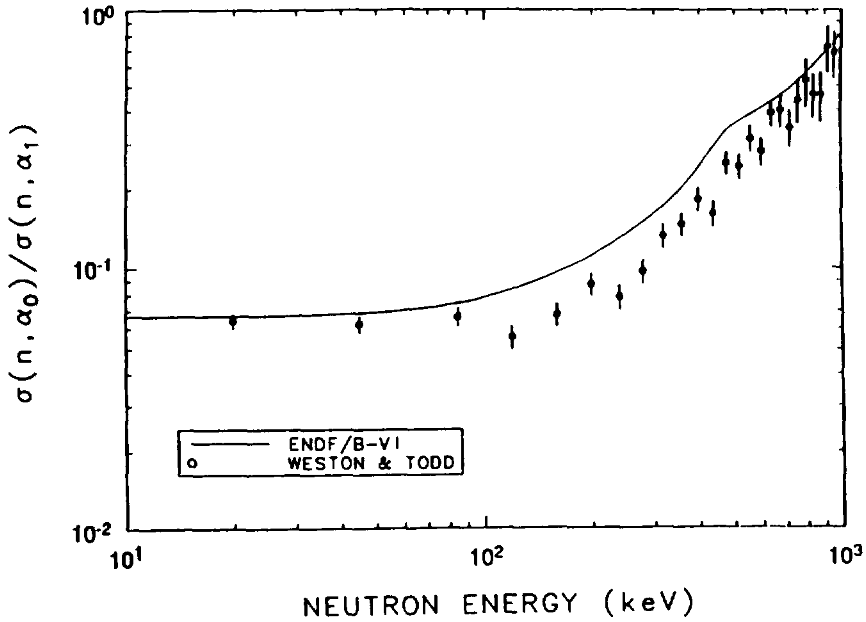

Fig. 1 Measurements of the branching ratio of ^{10}B cross sections by Weston and Todd [3] compared with the ENDF/B-VI evaluation.

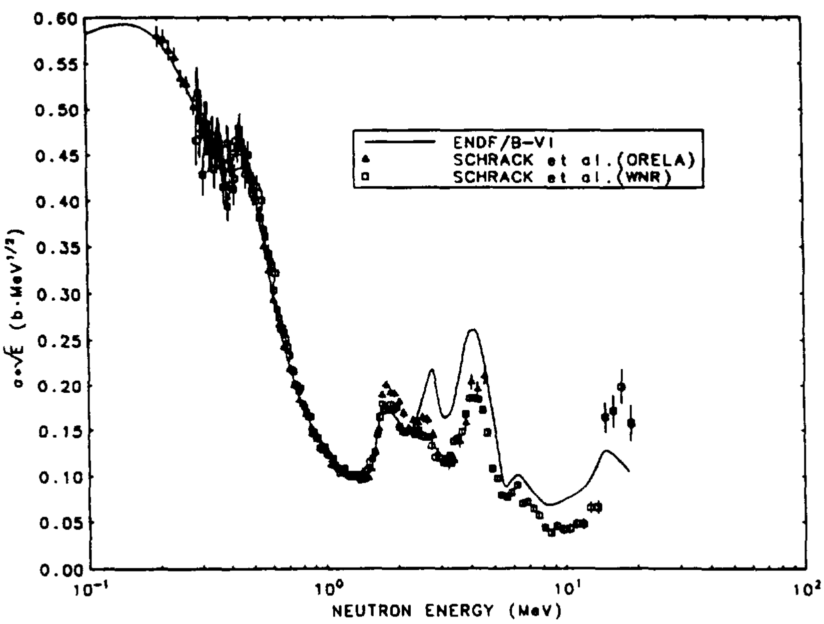

Fig. 2 Comparison of the $^{10}B(n,\alpha_1\gamma)$ cross section measurements of Schrack *et al.*, at ORELA [4] and WNR [5] facilities with the ENDF/B-VI evaluation.

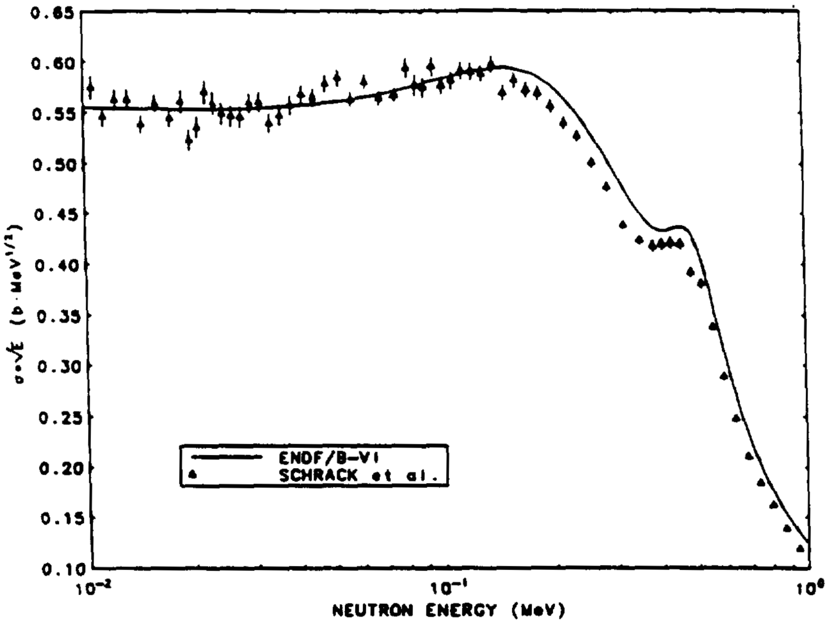

Fig. 3 Measurements of the $^{10}B(n,\alpha_1\gamma)$ cross section by Schrack *et al.* [6] compared with the ENDF/B-VI evaluation.

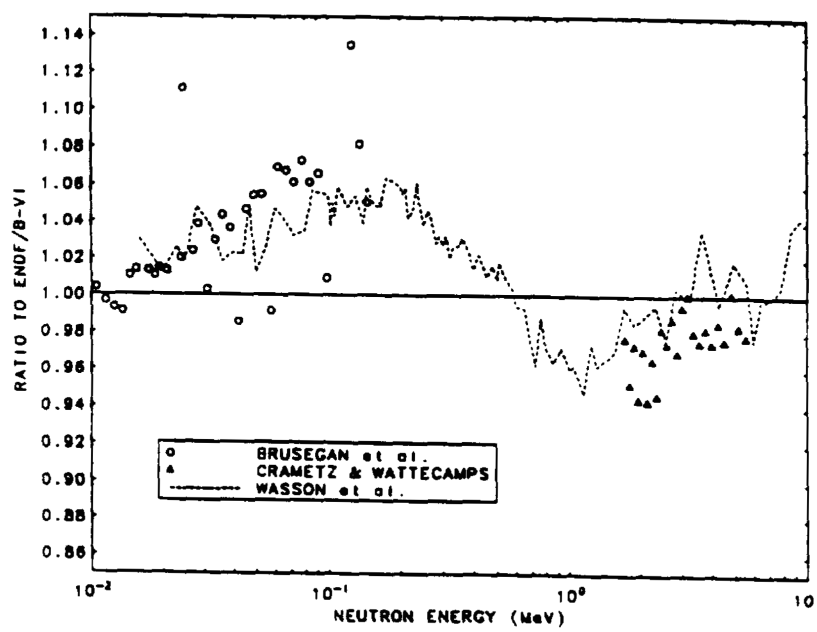

Fig. 4 Comparison of the recent measurements of the ^{10}B total cross section by Brusegan *et al.* [7], Crametz and Wattecamps [8], and Wasson *et al.* [9] with the ENDF/B-VI evaluation.

The ^{209}Bi(n,f) Cross Section

Introduction

The ^{209}Bi fission cross section is a useful standard in the neutron energy region above about 50 MeV for the following reasons:

a) the excitation function has a threshold of about 25 MeV which eliminates the influence of low energy neutrons;

b) there is a smooth variation of the cross section with neutron energy which makes it insensitive to neutron energy resolution;

c) ^{209}Bi is monoisotopic and a non-radioactive material. It is therefore easy to transport and handle.

Until recently only quite old data for the ^{209}Bi(n,f) cross section near 20-25 MeV were available. On the other hand an evaluation of the ^{209}Bi(n,f) cross section was made on the basis of a ^{209}Bi(p,f) cross section evaluation by Fukahori and Pearlstein [1], with the assumption that the ^{209}Bi(p,f)/ ^{209}Bi(n,f) cross section ratio is energy independent and is equal to 2. This evaluation is included in the ENDF/B-VI High Energy File.

Recently new experimental data became available. The goal of the present report is to suggest a revision of the ENDF/B-VI High Energy File based on these new experimental data as well as on a recent parameterization of the ^{209}Bi(p,f) cross section.

Status

Investigations of the neutron induced fission reaction in the intermediate energy region were started in the late forties and early fifties (Kelly, 1948 [2]; Reut, 1950 [3], Goldanski, 1955 [4]). The experimental equipment at that time did not allow high accuracy to be achieved. Consequently the data have large systematic errors due to the very wide and poorly known incident neutron energy spectrum, uncertainties in the beam monitoring, etc. The data obtained were more of a qualitative character.

A unique measurement of the subthreshold ^{209}Bi(n,f) cross section was made by Vorotnikov *et al.* [5] near 20 MeV. Due to the very small values of the ^{209}Bi(n,f) cross section in this energy region, the uncertainties are rather high (about 50%), but these data can serve to approximately show the trend of the ^{209}Bi(n,f) cross section in the low energy region up to the fission threshold.

In 1992 measurements of the (n,f) cross sections of heavy nuclei were started at the The Svedberg Laboratory in a collaboration between Uppsala University and the V.G. Khlopin Radium Institute. The (n,f) cross section measurements are carried out using time-of-flight techniques. The fission events are registered by means of non-traditional solid state fission chambers with thin-film breakdown counters (TFBC) for fission fragment detection. Recently absolute $^{209}Bi(n,f)$ cross sections and $^{209}Bi(n,f)/^{238}U(n,f)$ cross section ratios were measured at 45, 73, 96, 135 and 162 MeV [6-8]. At 135 MeV and 162 MeV the normalization of the $^{209}Bi(n,f)$ data was made using the H(n,n) cross section as a standard [6-8]. The rest of the data points were normalized using the $^{238}U(n,f)$ cross section data set of Lisowski *et al.* [9]. The accuracy of the absolute results is 13% and 10% at 135 MeV and 162 MeV, respectively. The accuracy of the relative measurements is about 10% in the 73 MeV to 162 MeV region and about 13% at 45 MeV.

At two neutron energies (45 and 73 MeV) simultaneous measurements of the $^{209}Bi(n,f)/^{238}U(n,f)$ relative cross section were carried out with the same neutron beam using a double Frisch gridded ionization chamber [10]. Good agreement with the above mentioned data was obtained.

All the absolute data and the evaluation from the ENDF/B-VI High Energy File are presented in figures 1a and 1b in semilogarithmic and logarithmic scales, respectively, in order to better display the different energy regions and data sets. Since these data may be difficult to obtain for the user community, they are given in Tables 1 through 4. Recently the $^{209}Bi(n,f)/^{235}U(n,f)$ cross section ratio was measured by Staples *et al.* [11] in the energy region from about 30 MeV to 450 MeV at the white neutron source at LANL. The data were normalized using the LANL $^{235}U(n,f)$ cross section [9]. At higher energies (above 168 MeV) a constant value of the $^{235}U(n,f)$ cross section was used. The preliminary results are in good agreement with the data from refs. [6-8,10] within the stated errors.

One can see from figure 1 that the ENDF/B-VI evaluation of the $^{209}Bi(n,f)$ cross section made by Fukahori and Pearlstein [1] lies 20 to 50% higher than the experimental data. It should be noted that the evaluation did not take into account the data of Vorotnikov *et al.* [5]. The evaluation needs to be revised. This should be done based on all published experimental $^{209}Bi(n,f)$ cross section data and the recent parameterization of the $^{209}Bi(p,f)$ cross section [12].

Also shown in figure 1 is the $^{209}Bi(p,f)$ parameterization of Prokofyev et al. [12]. This parameterization applies to a much larger energy range than is shown in this figure. The following general conclusions can be made from comparative analysis of the ^{209}Bi (p,f) and the $^{209}Bi(n,f)$ data:

1. The $^{209}Bi(p,f)$ cross section lies systematically higher than the $^{209}Bi(n,f)$ one at all energies, due to the higher value of the fissionability parameter (Z^2/A) of the compound system and the negligibly small influence of the Coulomb barrier for protons.

2. Both the $^{209}Bi(p,f)$ and $^{209}Bi(n,f)$ cross sections increase with incident particle energy up to about 400 MeV.

3. The $^{209}Bi(p,f)/^{209}Bi(n,f)$ cross section ratio changes with neutron energy and above about 300 MeV it approaches 2. Figure 2 shows the energy dependence of this ratio deduced from experimental data [4-8, 12] as well as a fit to the dependence [13].

In figure 1, a parameterization of the $^{209}Bi(n,f)$ cross section is presented (solid curve). It was obtained using the $^{209}Bi(p,f)$ parameterization [12] and the fit to the $^{209}Bi(p,f)/^{209}Bi(n,f)$ ratio [13] shown in figure 2. This parameterization is also presented in Table 5.

Recommendations

The existing experimental $^{209}Bi(n,f)$ cross section database is not yet sufficiently complete. To make an accurate evaluation of the $^{209}Bi(n,f)$ cross section, new experimental results are needed as well as new model calculations. Meanwhile it is recommended that the parameterization given in figure 1, as well as in Table 5, be used. Both a tabulation and analytical fits to the data are given in the table. The uncertainties on this parameterization are about 50 % at neutron energies from 20 MeV to 40 MeV; from 13 % at 40 MeV to 10 % at 160 MeV; and about 30 % above 169 MeV.

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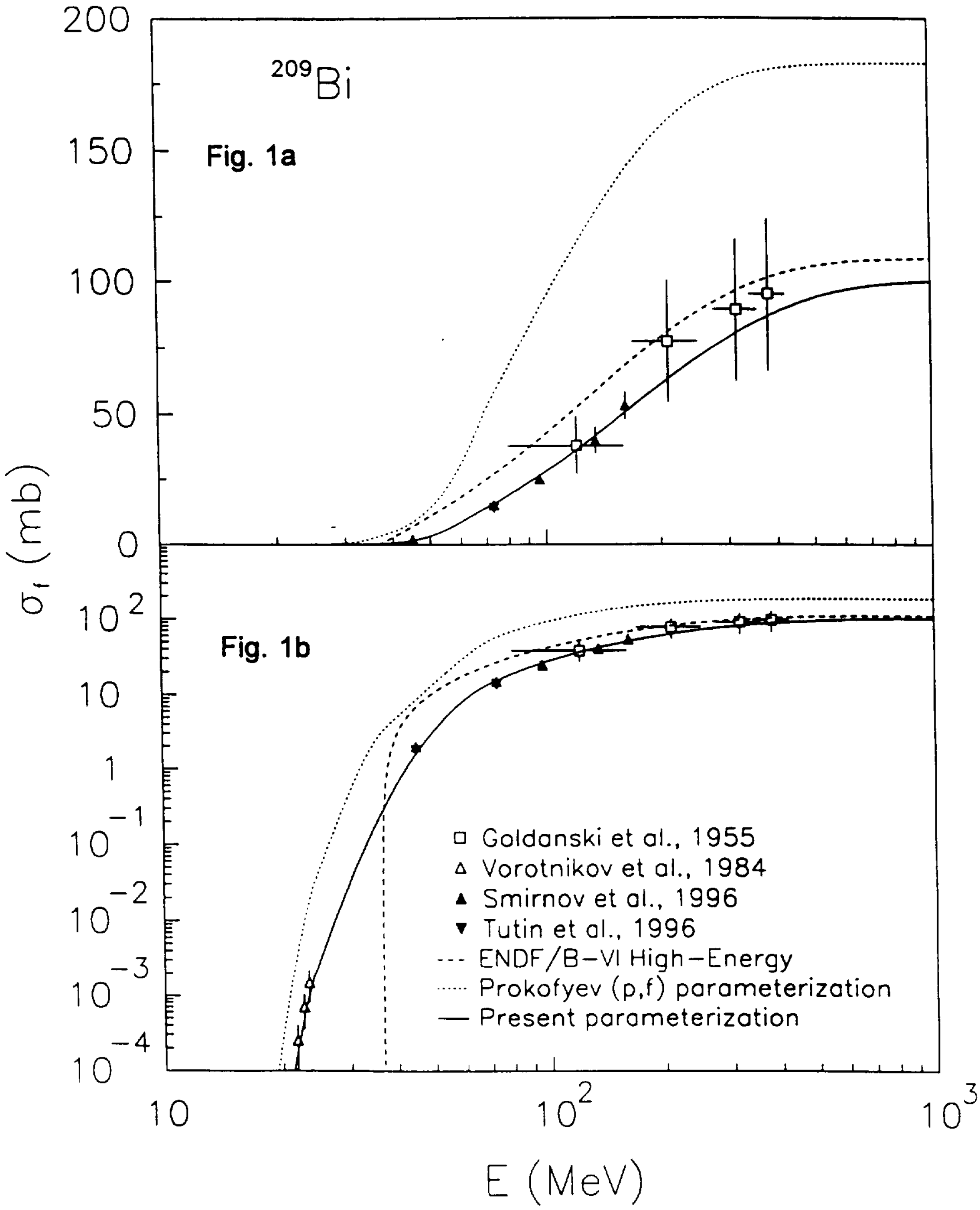

Fig. 1 Measurements of the $^{209}Bi(n,f)$ cross section compared with parameterizations and the ENDF/B-VI evaluation. For clarity the same data are shown with a semilogarithmic scale (Fig. 1a) and a logarithmic scale (Fig. 1b).

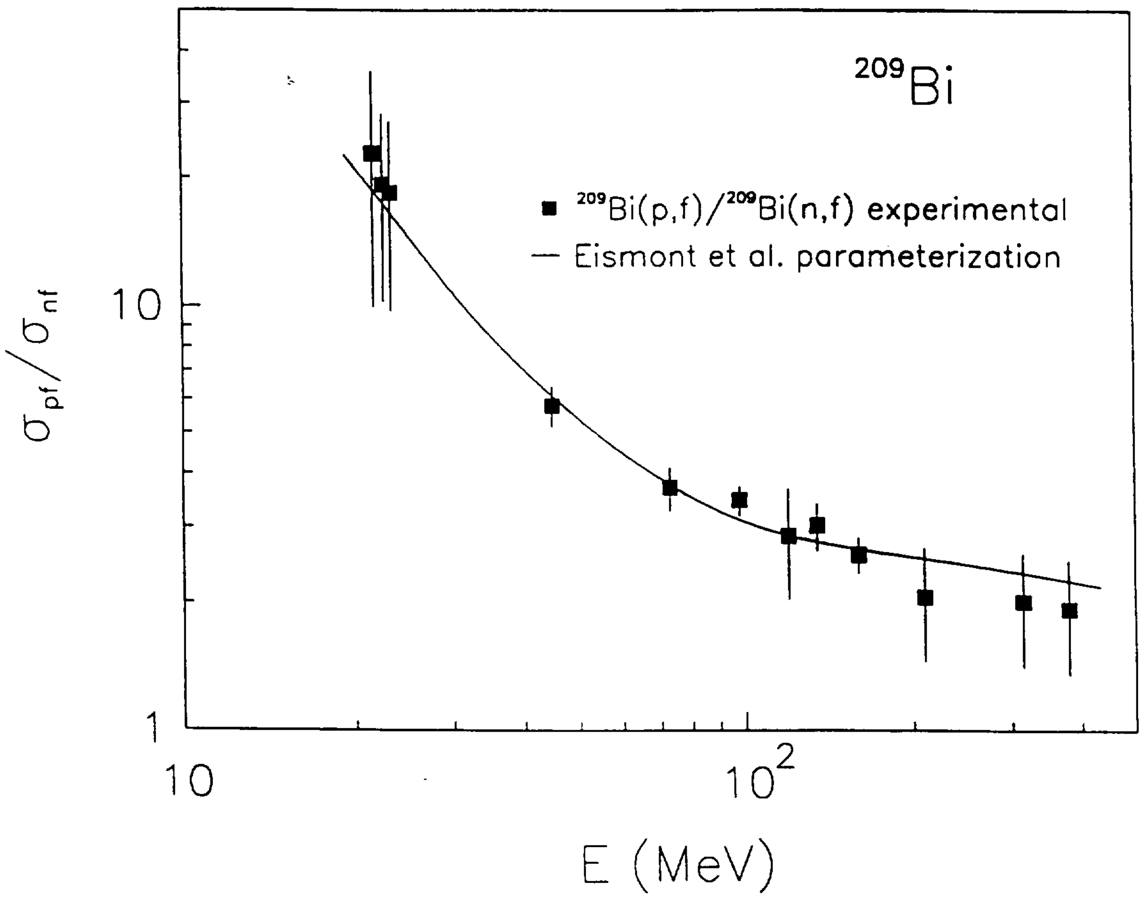

Fig. 2 The $^{209}Bi(p,f)/^{209}Bi(n,f)$ cross section ratio deduced from experimental (n,f) and (p,f) databases compared with the Eismont et al. parameterization [13].

Table 1. $^{209}Bi(n,f)$ Cross Section Data of Goldanski *et al.* [4]

Energy (MeV)	σ_{nf} (mb)	Uncertainty (%)
120	38	30
210	77	30
315	89	30
380	95	30

Table 2. $^{209}Bi(n,f)$ Cross Section Data of Vorotnikov *et al.* [5]

Energy (MeV)	σ_{nf} (mb)	Uncertainty (%)
18.0	<0.00003	-
21.7	0.00025	60
22.6	0.0007	50
23.3	0.0015	50

Table 3. $^{209}Bi(n,f)$ Cross Section Data of Smirnov *et al.* [6-8]

Energy (MeV)	σ_{nf} (mb)	Uncertainty (%)
45	2.0	13*
73	15	10*
96	25	8*
135	40	12.5
162	53	10

*The uncertainties do not include those of the $^{238}U(n,f)$ standard.

Table 4. $^{209}Bi(n,f)$ Cross Section Data of Tutin *et al.* [10]

Energy (MeV)	σ_{nf} (mb)	Uncertainty (%)
45	1.8	9*
73	13.9	14*

*The uncertainties do not include those of the $^{238}U(n,f)$ standard.

Table 5. ^{209}Bi(n,f) Cross Section Evaluation - Recommended Reference Data
$\sigma = \exp(-108.7 + 50(\ln E) - 5.6(\ln E)^2)$ for neutron energies from 20 MeV to 73 MeV.
$\sigma = 100(1 - \exp(-0.006(E - 45)))$ for neutron energies from 73 MeV to 1000 MeV.

Energy (MeV)	σ (mb)	Energy (MeV)	σ (mb)	Energy (MeV)	σ (mb)
21.0	0.000066	45.0	1.62	95.0	25.9
21.5	0.000138	46.0	1.91	96.0	26.4
22.0	0.000241	47.0	2.21	97.0	26.8
22.5	0.000446	48.0	2.55	98.0	27.2
23.0	0.000773	49.0	2.92	99.0	27.7
23.5	0.00117	50.0	3.32	100.0	28.1
24.0	0.00181	51.0	3.74	110.0	32.3
24.5	0.00233	53.0	4.67	120.0	36.2
25.0	0.00309	54.0	5.17	130.0	40.0
25.5	0.00407	55.0	5.69	140.0	43.4
26.0	0.00530	56.0	6.22	150.0	46.7
26.5	0.00684	57.0	6.78	160.0	49.8
27.0	0.00875	58.0	7.34	170.0	52.8
27.5	0.0111	59.0	7.92	180.0	55.5
28.0	0.0140	60.0	8.51	190.0	58.1
28.5	0.0175	61.0	9.09	200.0	60.5
29.0	0.0217	62.0	9.69	210.0	62.8
29.5	0.0267	63.0	10.3	220.0	65.0
30.0	0.0327	64.0	10.9	230.0	67.0
30.5	0.0397	65.0	11.4	240.0	69.0
31.0	0.0480	66.0	12.0	250.0	70.8
31.5	0.0576	67.0	12.6	260.0	72.5
32.0	0.0688	68.0	13.1	270.0	74.1
32.5	0.0817	69.0	13.6	280.0	75.6
33.0	0.0965	70.0	14.1	290.0	77.0
33.5	0.113	71.0	14.6	300.0	78.3
34.0	0.133	72.0	15.0	310.0	79.6
34.5	0.155	73.0	15.5	320.0	80.8
35.0	0.179	74.0	16.0	330.0	81.9
35.5	0.207	75.0	16.5	340.0	83.0
36.0	0.238	76.0	17.0	350.0	84.0
36.5	0.272	77.0	17.5	360.0	84.9
37.0	0.310	78.0	18.0	370.0	85.8
37.5	0.352	79.0	18.5	380.0	86.6
38.0	0.398	80.0	18.9	390.0	87.4
38.5	0.449	81.0	19.4	400.0	88.1
39.0	0.505	82.0	19.9	410.0	88.8
39.5	0.566	83.0	20.4	420.0	89.5
40.0	0.631	84.0	20.9	430.0	90.1
40.5	0.703	85.0	21.3	440.0	90.7
41.0	0.780	86.0	21.8	450.0	91.2
41.5	0.863	87.0	22.3	460.0	91.7
42.0	0.952	88.0	22.7		
42.5	1.05	89.0	23.2		
43.0	1.15	90.0	23.7		
43.5	1.26	92.0	24.6		
44.0	1.37	93.0	25.0		
44.5	1.50	94.0	25.5		

Table 5. $^{209}Bi(n,f)$ Cross Section Evaluation - Recommended Reference Data (Continued)
$\sigma = \exp(-108.7 + 50(\ln E) - 5.6(\ln E)^2)$ for neutron energies from 20 MeV to 73 MeV.
$\sigma = 100(1 - \exp(-0.006(E - 45)))$ for neutron energies from 73 MeV to 1000 MeV.

Energy (MeV)	σ (mb)	Energy (MeV)	σ (mb)	Energy (MeV)	σ (mb)
470.0	92.2	660.0	97.5	840.0	99.2
480.0	92.6	670.0	97.6	850.0	99.2
490.0	93.1	680.0	97.8	860.0	99.2
500.0	93.5	690.0	97.9	870.0	99.3
510.0	93.9	700.0	98.0	880.0	99.3
530.0	94.6	710.0	98.2	890.0	99.4
540.0	94.9	720.0	98.3	900.0	99.4
550.0	95.2	730.0	98.4	910.0	99.4
560.0	95.4	740.0	98.5	920.0	99.5
570.0	95.7	750.0	98.5	930.0	99.5
580.0	96.0	760.0	98.6	940.0	99.5
590.0	96.2	770.0	98.7	950.0	99.6
600.0	96.4	780.0	98.8	960.0	99.6
610.0	96.6	790.0	98.9	970.0	99.6
620.0	96.8	800.0	98.9	980.0	99.6
630.0	97.0	810.0	99.0	990.0	99.7
640.0	97.2	820.0	99.0	1000.0	99.7
650.0	97.3	830.0	99.1		

The ^{235}U Fission Cross Section

Introduction

The ^{235}U fission cross section is a good standard over the energy range 100 keV to 20 MeV and higher (up to hundreds of MeV) because:

a) the fission process has a high Q-value;

b) the cross section is of reasonable magnitude at all energies of interest;

c) ^{235}U is very suitable for use in fission chambers of different types. Fission foils can be assayed to high accuracy and ^{235}U has a long half life thus minimizing pulse pile-up and handling problems.

Recent results of measurements of the ^{235}U(n,f) cross section in the energy range above 20 MeV allow this standard to be extended to higher energies.

Status

The ^{235}U(n,f) cross section in the 15 MeV to 20 MeV energy range

Recent measurements of the ^{235}U(n,f) cross section [1-3] suggest that the ENDF/B-VI evaluation is in error in the energy region above 15 MeV neutron energy. In figure 1, these data are shown. Poenitz [4] has estimated the impact of measurements made since the ENDF/B-VI evaluation, but before 1992, on an evaluation of the ^{235}U(n,f) cross section. Figure 2 shows the percentage change that would occur if those measurements were added to that used in the ENDF/B-VI evaluation process. The data of Lisowski [3] are not included in this analysis.

The ^{235}U(n,f) cross section above 20 MeV

Measurements of the ^{235}U(n,f) cross section in the intermediate energy region (above ~20 MeV) were started in the fifties [5-6]. Until recently only these two data sets were published. Experimental equipment at that time did not allow one to achieve results with high accuracy. The data obtained were more qualitative in character. In the late eighties new experiments were started at the LANL intense neutron source, WNR, which has a white neutron spectrum extending up to about 800 MeV. Measurements of the ^{235}U(n,f) cross sections were carried out at this facility [2,3,7-9]. Time-of-flight techniques were used to cover the neutron energy range from 3 MeV to about 200 MeV. The neutron fluence monitoring was carried out with the use of plastic scintillators [7,8] as well as proton recoil spectrometers [2,3]. The measurements of the shape of the ^{235}U(n,f) cross section relative to the hydrogen scattering cross section were normalized to the very accurately known value of the ^{235}U(n,f) cross section near 14 MeV. The fission events were detected by means of multiplate fission ionization chambers.

Figure 3 shows the final results of the $^{235}U(n,f)$ cross section measurements of Lisowski *et al.* [9] for the energy range from 20 to 200 MeV. The data of Goldanski *et al.* [5] and Pankratov [6] are also presented in figure 3. One can see that there are considerable discrepancies between the data sets of Pankratov [6] and Lisowski *et al.* [3]. The measurement of Goldanski *et al.* [5] at 120 MeV is in good agreement with the Lisowski data.

Total uncertainties of the Lisowski *et al.* data are 2 % (at 30 MeV to 50 MeV), 3 % (at 50 MeV to 80 MeV), 4 % (at 80 MeV to 120 MeV) and 5 % (at 120 MeV to 200 MeV). The uncertainties include both statistical and systematic errors of the measurements and calculations of the efficiencies of the neutron fluence monitors. They do not include the uncertainty in the H(n,n) standard cross section. For this experiment the hydrogen scattering measurements were made at a center-of-mass scattering angle of 150° so the uncertainties in the hydrogen scattering cross section at back angles are largely removed.

Comments and Recommendations

Since the Lisowski $^{235}U(n,f)$ cross section data set above ~20 MeV is practically the only experimental data available, it is necessary to be sure that it is sufficiently reliable. The experimental data above 20 MeV were normalized to the very accurate data on the $^{235}U(n,f)$ cross section at ~14 MeV neutron energy. As can be seen from the figure, the $^{235}U(n,f)$ cross section decreases above about 30 MeV and then, near ~150 MeV, reaches approximately a constant value. According to recent qualitative comparisons of (p,f) and (n,f) cross sections for heavy nuclei carried out by Eismont *et al.* [10] the (p,f)/(n,f) cross sections ratios of heavy nuclei become constant at energies above ~150 MeV, and their values are different for different nuclei. On the other hand, recent detailed analyses of the existing (p,f) databases [11,12] have shown that the $^{235}U(p,f)$ cross sections of actinides (^{235}U, ^{238}U and ^{232}Th) decrease steadily with increasing incident proton energy above ~50 MeV up to 30 GeV. In figure 3 a parameterization of the $^{235}U(p,f)$ cross section data [12] is shown. One can see from the figure that the energy dependence of the $^{235}U(n,f)$ cross section represented by the data of Lisowski *et al.*, is not inconsistent with the slope of the $^{235}U(p,f)$ cross section within the experimental errors. However, final conclusions require further analyses of the experimental $^{235}U(p,f)$ database as well as further measurements of the $^{235}U(n,f)$ cross sections in the higher energy range. It is also necessary that new $^{235}U(n,f)$ cross section results be obtained at high neutron energies using other independent experimental techniques. One possibility would be to make measurements with quasimonoenergetic neutron sources.

The Lisowski data has been internally evaluated at LANL for use at the WNR facility. Since the $^{235}U(n,f)$ cross section is a very important standard at high neutron energies, it is recommended that the values of this cross section used at that facility be used until new evaluations of the cross section are available. These values are given in Table 1. Also given in this table are analytical fits to the tabular data which agree with them to about 0.1%. Since these data are based on the Lisowski measurements, the total uncertainties are about 2 % (for 30 MeV to 50 MeV), 3 % (for 50 MeV to 80 MeV), 4 % (for 80 MeV to 120 MeV) and 5 % (for 120 MeV to 200 MeV). They do not include the uncertainty in the H(n,n) standard cross section.

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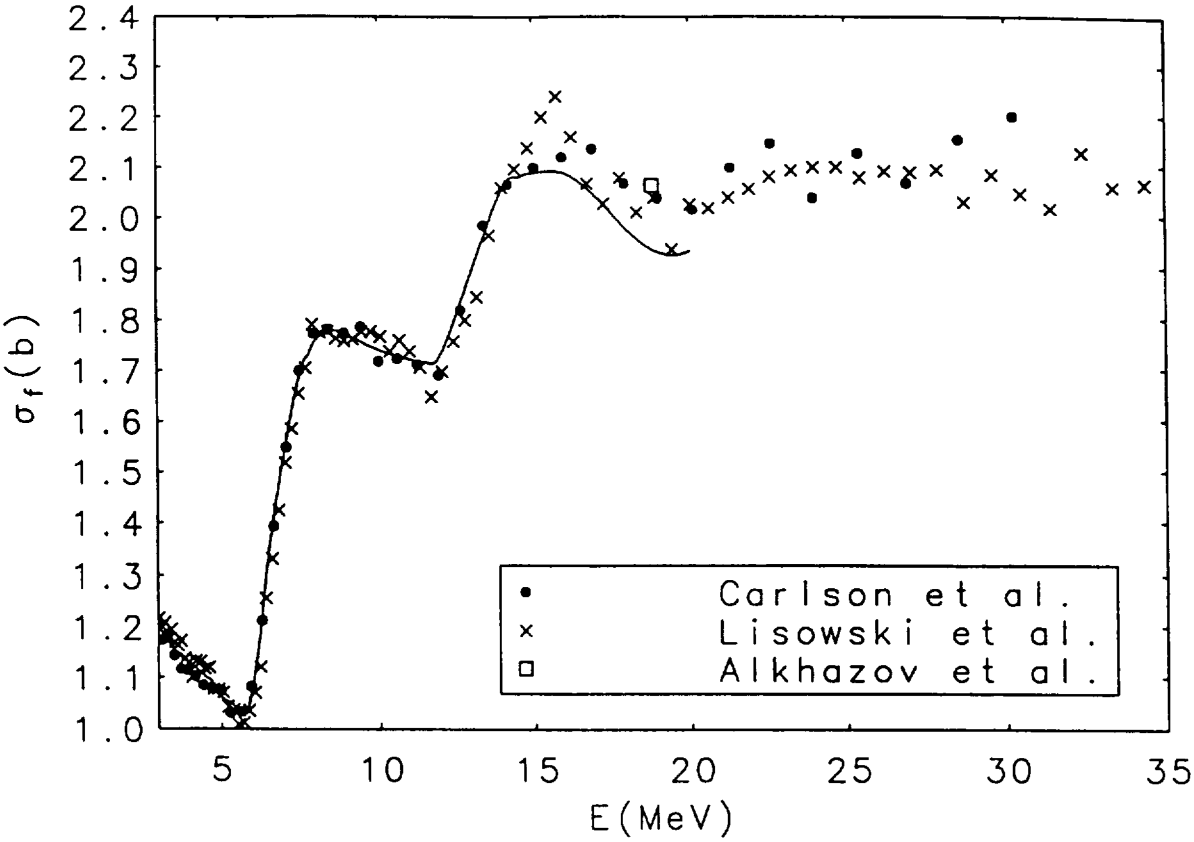

Fig. 1 Recent measurements of the $^{235}U(n,f)$ cross section compared with the ENDF/B-VI evaluation.

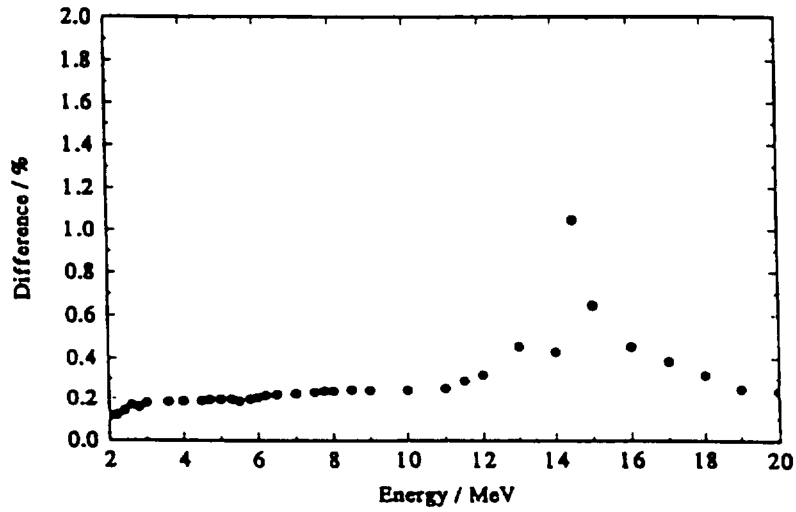

Fig. 2 The change in an evaluated $^{235}U(n,f)$ cross section as a result of new experimental data obtained since the ENDF/B-VI evaluation and before 1992.

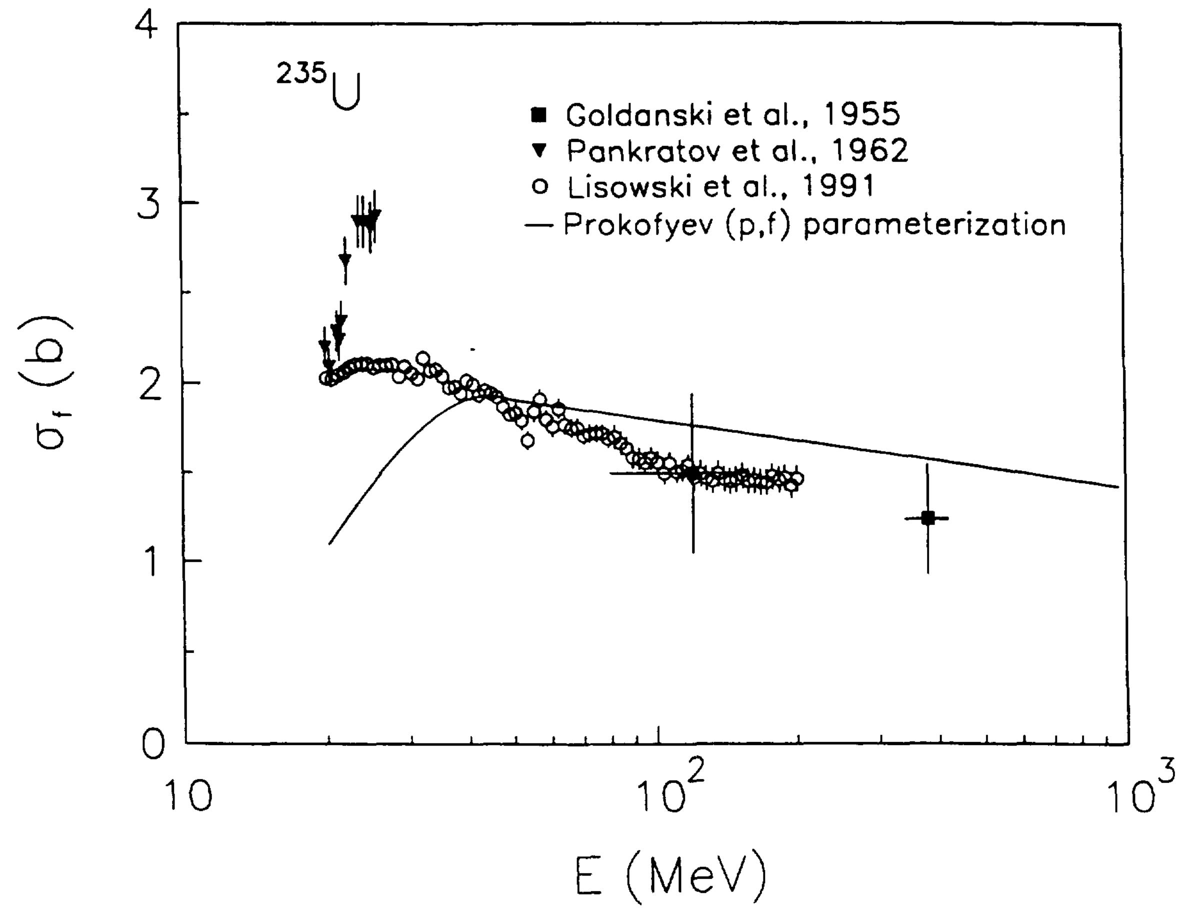

Fig. 3 Comparison of measurements of the ^{235}U(n,f) cross section above 20 MeV neutron energy with the ^{235}U(p,f) parameterization of Prokofyev [12].

Table 1. The $^{235}U(n,f)$ cross section above 20 MeV - Recommended Reference Data

$$\sigma = \Sigma\, a(N)E^{N-1}$$

20.00 MeV < E < 22.259 MeV; a(1) = 42.7166, a(2) = -7.62357, a(3) = 0.538579, a(4) = -0.0170663, a(5) = 2.05374E-04

22.259 MeV < E < 26.15 MeV; a(1) = 1162.3369, a(2) = -272.40531, a(3) = 26.499823, a(4) = -1.3679508, a(5) = 0.039538964, a(6) = -6.0695972E-04, a(7) = 3.8673095E-06

26.15 MeV < E < 62.95 MeV; a(1) = -2.02908, a(2) = 0.521141, a(3) = -0.0257918, a(4) = 6.44748E-04, a(5) = -8.77333E-06, a(6) = 6.18946E-08, a(7) = -1.77344E-10

62.95 MeV < E < 134.1 MeV; a(1) = 1.40538, a(2) = 0.0301602, a(3) = -6.04041E-04, a(4) = 4.09073E-06, a(5) = -9.27097E-09

134.1 MeV < E < 200.0 MeV; a(1) = 1.46724, a(2) = -9.71941E-05

Energy (MeV)	**σ (b)**	**Energy (MeV)**	**σ (b)**	**Energy (MeV)**	**σ (b)**	**Energy (MeV)**	**σ (b)**
20.5	2.0143	36.0	2.0078	53.0	1.8578	84.0	1.6397
21.0	2.0256	36.5	2.0024	54.0	1.8506	85.0	1.6331
21.5	2.0403	37.0	1.9969	55.0	1.8435	86.0	1.6265
22.0	2.0584	37.5	1.9915	56.0	1.8363	87.0	1.6200
22.5	2.0759	38.0	1.9862	57.0	1.8291	88.0	1.6135
23.0	2.0866	38.5	1.9809	58.0	1.8218	89.0	1.6072
23.5	2.0936	39.0	1.9756	59.0	1.8145	90.0	1.6009
24.0	2.0972	39.5	1.9705	60.0	1.8071	91.0	1.5948
24.5	2.0979	40.0	1.9654	61.0	1.7997	92.0	1.5887
25.0	2.0963	40.5	1.9604	62.0	1.7922	93.0	1.5828
25.5	2.0934	41.0	1.9554	63.0	1.7847	94.0	1.5770
26.0	2.0898	41.5	1.9506	64.0	1.7783	95.0	1.5713
26.5	2.0879	42.0	1.9458	65.0	1.7716	96.0	1.5657
27.0	2.0870	42.5	1.9412	66.0	1.7649	97.0	1.5602
27.5	2.0849	43.0	1.9366	67.0	1.7581	98.0	1.5549
28.0	2.0828	43.5	1.9321	68.0	1.7512	99.0	1.5497
28.5	2.0798	44.0	1.9276	69.0	1.7443	100.0	1.5446
29.0	2.0767	44.5	1.9233	70.0	1.7373	110.0	1.5015
29.5	2.0729	45.0	1.9190	71.0	1.7303	120.0	1.4728
30.0	2.0691	45.5	1.9148	72.0	1.7233	130.0	1.4574
30.5	2.0647	46.0	1.9107	73.0	1.7162	140.0	1.4536
31.0	2.0603	46.5	1.9067	74.0	1.7092	150.0	1.4527
31.5	2.0554	47.0	1.9026	75.0	1.7021	160.0	1.4517
32.0	2.0506	47.5	1.8987	76.0	1.6950	170.0	1.4507
32.5	2.0454	48.0	1.8948	77.0	1.6880	180.0	1.4497
33.0	2.0403	48.5	1.8909	78.0	1.6810	190.0	1.4488
33.5	2.0350	49.0	1.8871	79.0	1.6740	200.0	1.4478
34.0	2.0297	49.5	1.8834	80.0	1.6670		
34.5	2.0243	50.0	1.8796	81.0	1.6601		
35.0	2.0188	51.0	1.8723	82.0	1.6533		
35.5	2.0133	52.0	1.8650	83.0	1.6465		

The $^{238}U(n,f)$ Cross Section

Introduction

The ^{238}U fission cross section is a useful standard in the MeV energy region for the following reasons:

a) the excitation function has a threshold near 1 MeV which eliminates the influence of low energy neutrons;

b) there is a smooth variation of the cross section with neutron energy which makes it insensitive to the neutron energy resolution;

c) it has a relatively large cross section which facilitates measurements of neutron fluence;

d) the availability of well developed fission chambers of different types and data-handling-techniques increase the reliability of those measurements.

Status

The $^{238}U(n,f)$ cross section in the 15 MeV to 20 MeV energy range

Recent measurements of the $^{235}U(n,f)$ cross section and the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio [1-6] suggest that there should be a change in the $^{238}U(n,f)$ cross section between 15 MeV and 20 MeV compared with the ENDF/B-VI evaluation. In figure 1, recent measurements of Lisowski *et al.*[4], Merla *et al.* [5] and Winkler *et al.* [6] are shown. The impact of measurements made since the ENDF/B-VI evaluation, but before 1992, on an evaluation of the $^{238}U(n,f)$ cross section has been determined by Poenitz [7]. Figure 2 shows the percentage change that would occur if the data from these experiments were added to that used in the ENDF/B-VI evaluation process. The change in the cross section is effected by new measurements of the $^{238}U(n,f)$ cross section as well as new data which are correlated to that cross section. The data of Lisowski *et al.* [4] are not included in that analysis.

The $^{238}U(n,f)$ cross section above 20 MeV

Measurements of the $^{238}U(n,f)$ cross section in the intermediate energy region (above 20 MeV to 30 MeV) were started in the 1950's [8-11]. Until recently only a few data sets were published. The experimental equipment used in the earliest measurements did not allow one to achieve high accuracy; the data obtained were more qualitative in character.

Measurements of the $^{238}U(n,f)/\ ^{235}U(n,f)$ cross section ratio were carried out at the LAMPF/WNR facility by Lisowski *et al.* [1-4]. Time-of-flight techniques were used to cover the neutron energy range from 0.8 to about 400 MeV. The fission events were detected by means of multiplate fission ionization chambers. Simultaneous with these measurements, the shape of the ^{235}U(n,f) cross section was determined from the fission rate in the ^{235}U deposits and measurements of the neutron fluence with proton recoil spectrometers. The ^{235}U(n,f) cross section was normalized to the very accurately known value of the ^{235}U(n,f) cross section at 14 MeV.

A few series of ^{238}U(n,f)/^{235}U(n,f) cross section ratio measurements were carried out at the white neutron spectrum facility "GNEIS" in Gatchina (St. Petersburg Institute of Nuclear Physics, Russia) [12,13]. Time-of-flight techniques were used to cover the neutron energy range from 0.5 to about 200 MeV. The fission events were detected by means of a multiplate fission ionization chamber.

In 1992 measurements of the (n,f) cross sections of heavy nuclei were started at the quasimonoenergetic neutron beam facility at the The Svedberg Laboratory in a collaboration between Uppsala University and the V.G. Khlopin Radium Institute. 50 MeV to 160 MeV neutrons were produced by the ^{7}Li(p,n) reaction. The neutron spectrum has a full energy peak, containing about 30-50 % of the neutrons, and an almost constant tail of lower energy neutrons. An important advantage at this facility is the availability of a unique magnet proton recoil spectrometer "LISA" which allows information to be obtained about the neutron spectrum and the neutron fluence based on the H(n,n) standard cross section. The (n,f) cross section measurements are carried out using time-of-flight techniques. The fission events are registered by means of non-traditional solid state fission chambers with thin-film breakdown counters (TFBC) for fission fragment detection. Recently the absolute ^{238}U(n,f) cross section was measured at 135 and 162 MeV [14-16].

In figure 3 the final ^{238}U(n,f)/^{235}U(n,f) cross section ratio data obtained by Lisowski *et al.* [3] is presented as well as the most recent preliminary data set obtained at the "GNEIS" facility [13]. It can be seen that the data sets are in agreement in the neutron energy range 20 MeV to 200 MeV within the stated errors. The general conclusion from the analysis of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio is that it becomes constant at neutron energies above about 100 MeV. As was shown in ref. [3], the same trend is observed for other uranium isotopes also.

^{238}U(n,f) cross section data were obtained by Lisowski *et al.* [2,4] from their ratio measurements and their determinations of the ^{235}U(n,f) cross section. Figure 4 shows the final data set of Lisowski *et al.* [4] for neutron energies above 20 MeV as well as the results of the measurements of Smirnov *et al.* at Uppsala (135 and 160 MeV) [15-16], the results of Goldanski *et al.* [8] (120±40 MeV and 380±40 MeV) and part of the data of Pankratov [9] from 20 MeV to 37 MeV. These two latter data sets should be considered only as very qualitative. They are discrepant with respect to the rest of the data.

The uncertainties shown in figure 3 for the data of Lisowski *et al.* [4] are purely statistical. The total uncertainties of the data obtained at the Uppsala facility [15-16] are about 10 %, of which the main part (8 %) is the sum of the errors connected with the measurement of the neutron fluence and the neutron beam profile.

One can see from the figure that the data obtained by different groups using completely different experimental techniques [4,15] are in good agreement within the experimental errors.

Comments and Recommendations

It is necessary to be sure that the data sets presented above are sufficiently reliable. The $^{238}U(n,f)$ cross section data above 20 MeV obtained in ref. [4] were obtained from absolute measurements of the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio combined with measurements of the $^{235}U(n,f)$ cross section normalized to the very accurate data at 14 MeV neutron energy. The data at 135 MeV and 162 MeV obtained in ref. [15] were normalized to the H(n,n) scattering cross section. The agreement between these data and those of Lisowski *et al.* [4] is very important and supports their reliability. On the other hand, as is seen from the figure, the $^{238}U(n,f)$ cross section decreases above 20 to 30 MeV and then, near about 150 MeV, reaches an approximately constant value. According to a recent qualitative comparison of (p,f) and (n,f) cross sections for heavy nuclei carried out by Eismont *et al.* [17] the (p,f)/(n,f) cross section ratios of heavy nuclei become constant at energies above 150 to 200 MeV, and the values are different for different nuclei. A recent detailed analysis of the existing (p,f) database [18-19] has shown that the (p,f) cross section of actinides (^{235}U, ^{238}U and ^{232}Th) decreases steadily with increasing incident proton energy from above 50 to 100 MeV up to 30 GeV. In figure 4 a representation of the $^{238}U(p,f)$ cross section data [19] is shown. One can see that the energy dependence of the $^{238}U(n,f)$ cross section represented by the data of Lisowski *et al.*, does not disagree with the slope of the (p,f) cross section, if the total uncertainties of these $^{238}U(n,f)$ cross section data are taken into account, including the uncertainties in the $^{235}U(n,f)$ cross section relative to which this cross section was measured. However, to make a final conclusion, further analyses of the experimental $^{238}U(p,f)$ database as well as further measurements of the $^{238}U(n,f)$ cross section in the higher energy range are necessary. Until a proper evaluation of the cross section is available, it is recommended that the cross section ratio of Lisowski *et al.* [4] be used. These data are given in Table 1. Also given in Table 1 are analytical fits to the cross section which can be used to calculate the cross section at arbitrary energies. In Table 2 the $^{238}U(n,f)$ cross sections are given. These cross sections were calculated from the tabular ratio data given in Table 1 and the tabular $^{235}U(n,f)$ cross section data given in Table 1 of the section on the $^{235}U(n,f)$ standard. The total uncertainties are about 2 % (for 30 MeV to 50 MeV), 3 % (for 50 MeV to 80 MeV), 4 % (for 80 MeV to 120 MeV) and 5 % (for 120 MeV to 200 MeV). They do not include the uncertainty in the H(n,n) standard cross section.

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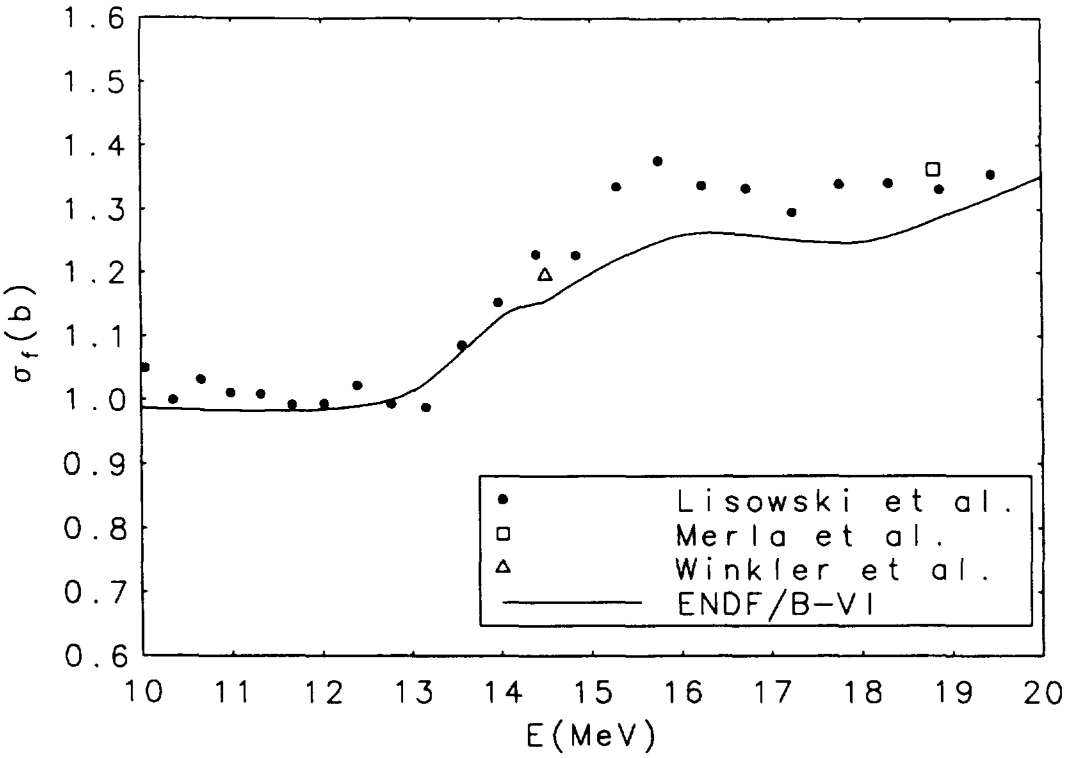

Fig. 1 Recent measurements of the $^{238}U(n,f)$ cross section compared with the ENDF/B-VI evaluation.

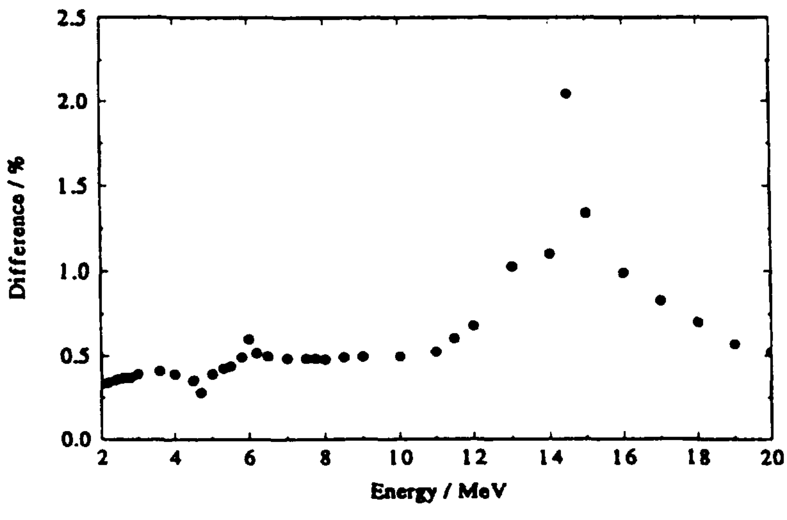

Fig. 2 The change in an evaluation of the $^{238}U(n,f)$ cross section as a result of new experimental data obtained since the ENDF/B-VI evaluation and before 1992.

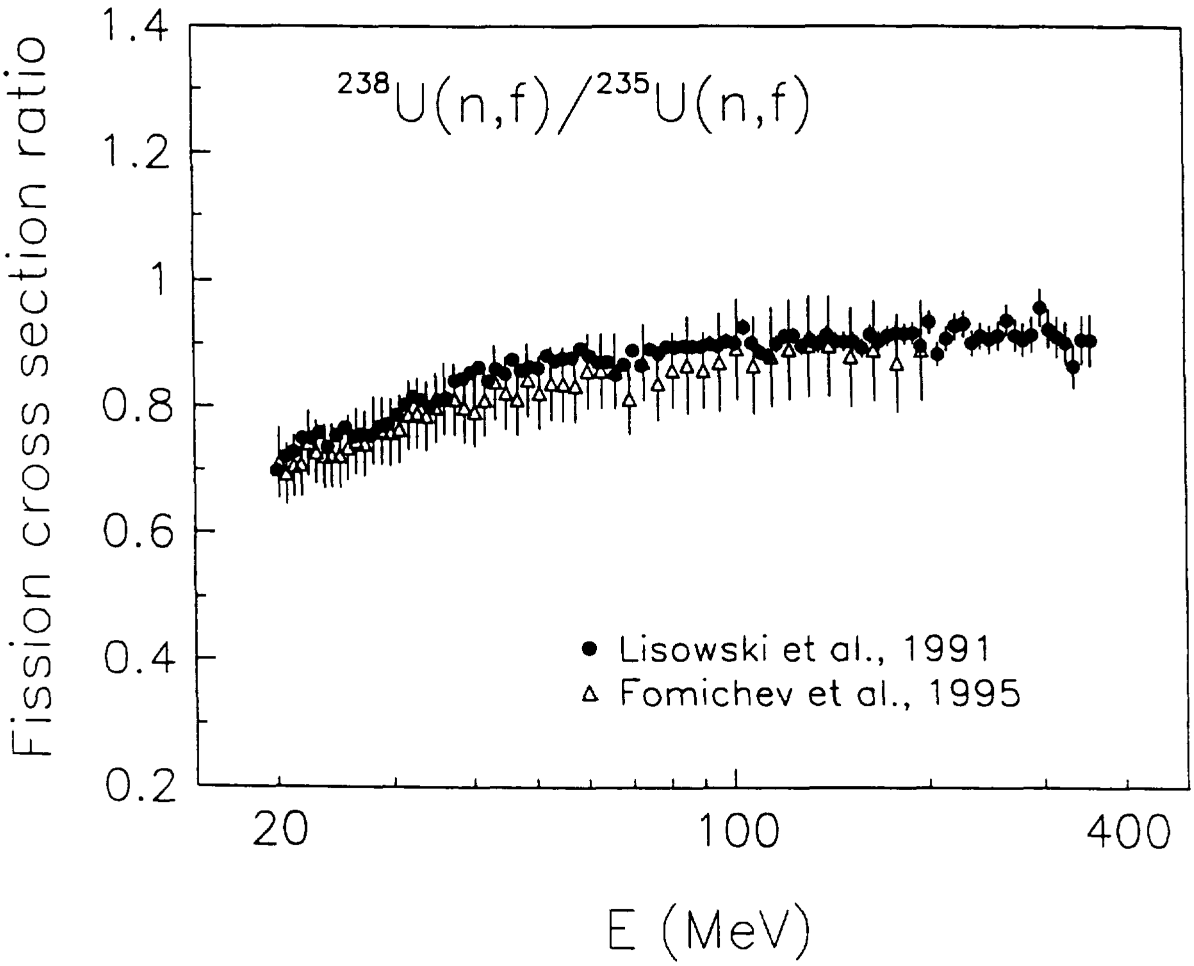

Fig. 3 Recent measurements of the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio above 20 MeV neutron energy.

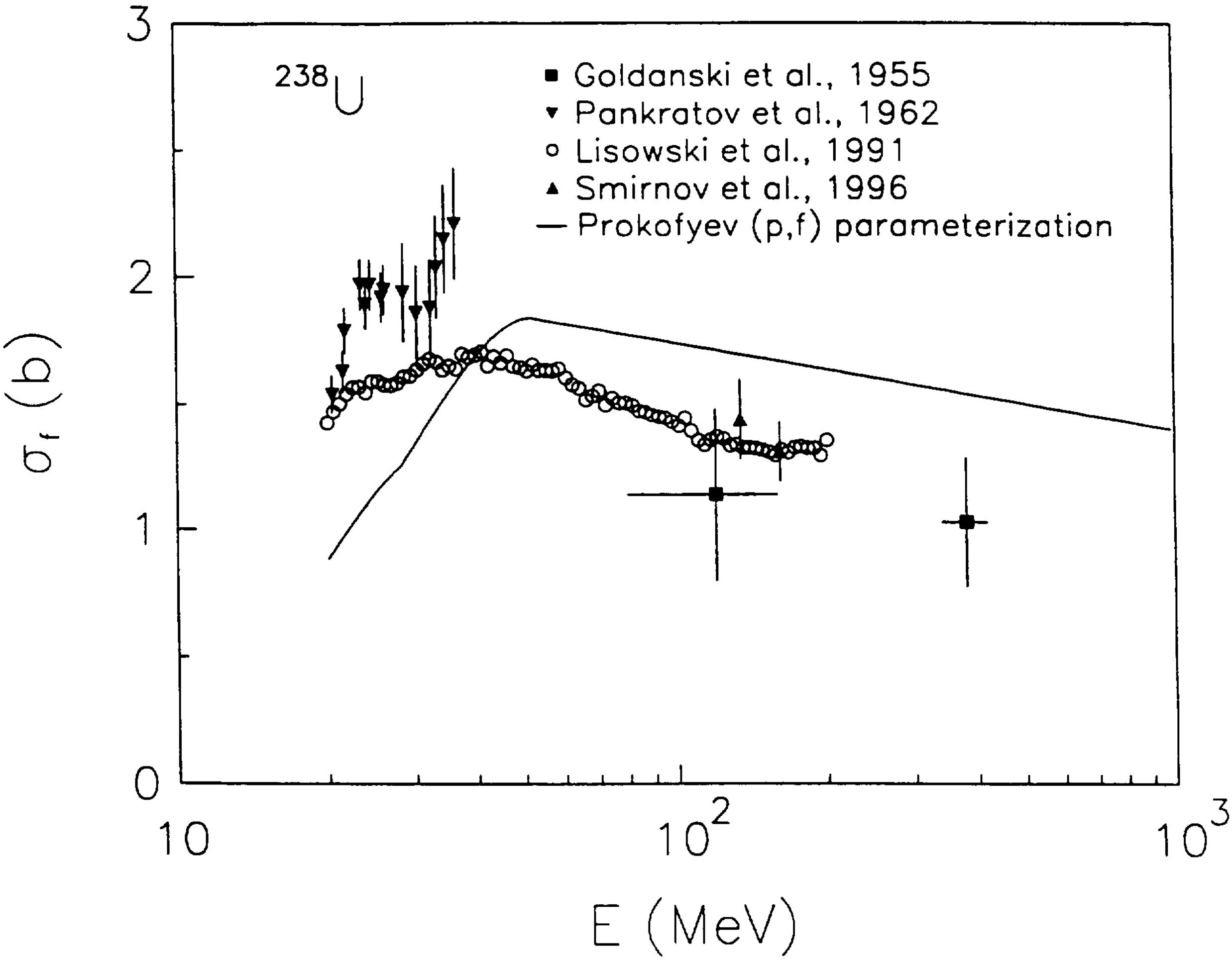

Fig. 4 Measurements of the ^{238}U(n,f) cross section compared with the ^{238}U(p,f) parameterization of Prokofyev [19]

Table 1 $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio above 20 MeV

- Recommended Reference Data -

$R = \Sigma\, a(N)E^{N-1}$ for 20 MeV < E < 30 MeV; a(1) = -1.8415050, a(2) = 0.29048799,
a(3) = -0.010901993, a(4) = 1.3761431E-04

R =A(1-exp(-E/B)) + C(1-exp(-E/D)) for E > 30 MeV; A = 0.8119, B = 13.88724,
C = 0.09563, D = 30.65851

Energy (MeV)	Ratio	Energy (MeV)	Ratio	Energy (MeV)	Ratio	Energy (MeV)	Ratio
20.5	0.7175	37.5	0.8248	59.0	0.8820	93.0	0.9019
21.0	0.7254	38.0	0.8272	60.0	0.8832	94.0	0.9021
21.5	0.7322	38.5	0.8295	61.0	0.8844	95.0	0.9024
22.0	0.7380	39.0	0.8318	62.0	0.8855	96.0	0.9026
22.5	0.7429	39.5	0.8339	63.0	0.8866	97.0	0.9027
23.0	0.7469	40.0	0.8360	64.0	0.8876	98.0	0.9029
23.5	0.7503	40.5	0.8381	65.0	0.8885	99.0	0.9031
24.0	0.7530	41.0	0.8400	66.0	0.8894	100.0	0.9033
24.5	0.7553	41.5	0.8419	67.0	0.8903	110.0	0.9046
25.0	0.7572	42.0	0.8438	68.0	0.8911	120.0	0.9055
25.5	0.7588	42.5	0.8456	69.0	0.8918	130.0	0.9061
26.0	0.7601	43.0	0.8473	70.0	0.8925	140.0	0.9065
26.5	0.7615	43.5	0.8490	71.0	0.8932	150.0	0.9068
27.0	0.7628	44.0	0.8506	72.0	0.8939	160.0	0.9070
27.5	0.7642	44.5	0.8522	73.0	0.8945	170.0	0.9072
28.0	0.7659	45.0	0.8537	74.0	0.8950	180.0	0.9073
28.5	0.7679	45.5	0.8552	75.0	0.8956	190.0	0.9073
29.0	0.7704	46.0	0.8566	76.0	0.8961	200.0	0.9074
29.5	0.7733	46.5	0.8580	77.0	0.8966	210.0	0.9074
30.0	0.7769	47.0	0.8594	78.0	0.8971	220.0	0.9075
30.5	0.7819	47.5	0.8607	79.0	0.8975	230.0	0.9075
31.0	0.7856	48.0	0.8619	80.0	0.8979	240.0	0.9075
31.5	0.7893	48.5	0.8632	81.0	0.8983	250.0	0.9075
32.0	0.7928	49.0	0.8644	82.0	0.8987	260.0	0.9075
32.5	0.7962	49.5	0.8655	83.0	0.8991	270.0	0.9075
33.0	0.7995	50.0	0.8666	84.0	0.8994	280.0	0.9075
33.5	0.8027	51.0	0.8688	85.0	0.8998	290.0	0.9075
34.0	0.8058	52.0	0.8708	86.0	0.9001	300.0	0.9075
34.5	0.8088	53.0	0.8727	87.0	0.9004	310.0	0.9075
35.0	0.8117	54.0	0.8745	88.0	0.9007	320.0	0.9075
35.5	0.8145	55.0	0.8762	89.0	0.9010	330.0	0.9075
36.0	0.8172	56.0	0.8777	90.0	0.9012	340.0	0.9075
36.5	0.8198	57.0	0.8792	91.0	0.9015	350.0	0.9075
37.0	0.8224	58.0	0.8806	92.0	0.9017		

Table 2. The $^{238}U(n,f)$ cross section above 20 MeV - Recommended Reference Data

Energy (MeV)	σ (b)	Energy (MeV)	σ (b)	Energy (MeV)	σ (b)	Energy (MeV)	σ (b)
20.5	1.4453	35.5	1.6398	51.0	1.6267	81.0	1.4913
21.0	1.4694	36.0	1.6408	52.0	1.6240	82.0	1.4858
21.5	1.4939	36.5	1.6416	53.0	1.6213	83.0	1.4804
22.0	1.5191	37.0	1.6423	54.0	1.6183	84.0	1.4747
22.5	1.5422	37.5	1.6426	55.0	1.6153	85.0	1.4695
23.0	1.5585	38.0	1.6430	56.0	1.6117	86.0	1.4640
23.5	1.5708	38.5	1.6432	57.0	1.6081	87.0	1.4586
24.0	1.5792	39.0	1.6433	58.0	1.6043	88.0	1.4533
24.5	1.5845	39.5	1.6432	59.0	1.6004	89.0	1.4481
25.0	1.5873	40.0	1.6431	60.0	1.5960	90.0	1.4427
25.5	1.5885	40.5	1.6430	61.0	1.5917	91.0	1.4377
26.0	1.5885	41.0	1.6425	62.0	1.5870	92.0	1.4325
26.5	1.5899	41.5	1.6422	63.0	1.5823	93.0	1.4275
27.0	1.5920	42.0	1.6419	64.0	1.5784	94.0	1.4226
27.5	1.5933	42.5	1.6415	65.0	1.5741	95.0	1.4179
28.0	1.5952	43.0	1.6409	66.0	1.5697	96.0	1.4132
28.5	1.5971	43.5	1.6404	67.0	1.5652	97.0	1.4084
29.0	1.5999	44.0	1.6396	68.0	1.5605	98.0	1.4039
29.5	1.6030	44.5	1.6390	69.0	1.5556	99.0	1.3995
30.0	1.6075	45.0	1.6383	70.0	1.5505	100.0	1.3952
30.5	1.6144	45.5	1.6375	71.0	1.5455	110.0	1.3583
31.0	1.6186	46.0	1.6367	72.0	1.5405	120.0	1.3336
31.5	1.6223	46.5	1.6359	73.0	1.5351	130.0	1.3206
32.0	1.6257	47.0	1.6351	74.0	1.5297	140.0	1.3177
32.5	1.6285	47.5	1.6342	75.0	1.5244	150.0	1.3173
33.0	1.6312	48.0	1.6331	76.0	1.5189	160.0	1.3167
33.5	1.6335	48.5	1.6322	77.0	1.5135	170.0	1.3161
34.0	1.6355	49.0	1.6312	78.0	1.5080	180.0	1.3153
34.5	1.6373	49.5	1.6301	79.0	1.5024	190.0	1.3145
35.0	1.6387	50.0	1.6289	80.0	1.4968	200.0	1.3137

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