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REVIEW OF STANDARD REFERENCE DATA AND IMPORTANT CROSS SECTION DISCREPANCIES

November 1976

A Report of the NEANDC Subcommittee on Standards and Discrepancies

H. E. Jackson, Chairman
Physics Division

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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H. E. Jackson, Chairman
K. H. Bockhoff
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Abstract

The proposal of a standing status file on standard reference data and major data discrepancies under the joint maintenance of the NEA Nuclear Data Committee and the International Nuclear Data Committee of the IAEA has been adopted. National responsibilities have been assigned for a standard reference data set and a file of important data discrepancies. Initial entries to the reference data set are reported. Entries to the discrepancy file are also presented. Analysis and evaluation of several entries is in progress and the file will be updated on a continuing basis as new information is received.

I. Introduction

Measurement of nuclear cross sections and related nuclear data has been a vital element of research in support of nuclear energy programs of the countries in the NEA. In the past, certain basic cross sections were needed to discuss conceptual designs of energy systems, to evaluate the performance of critical assemblies, for sensitivity studies, etc., and to develop neutronic models which could be used to design parameters for fission energy systems. In recent years fission reactor programs have evolved from the early research phase, through the developmental stage to the present efforts directed toward the construction of demonstration systems. The needs for nuclear data have undergone a similar change in character. Whereas earlier primary concern was in nuclear cross sections relevant to operating parameters for fission reactors, a substantial portion of the requests for nuclear data now are justified in their relevance to problems of reactor safety, waste disposal, and improved fuel economy. In addition in recent years new needs have developed for nuclear data in support of the growing research and development in controlled fusion reactions. Clearly nuclear data measurements of improved precision and in new areas continue to be an important part of energy research.

The current needs of the various national energy programs and other technologies for nuclear data are summarized in various national and international compilations of nuclear data requests (e.g. see WRENDA 76/77, INDC (SEC)-55/URSF, August 1976). However within the activities directed at meeting these needs there are problem areas involving data for which there is an urgent need, but for which the existing measurements are clearly discrepant. In addition, limitations in measurement precision are frequently imposed by the standard reference data employed. It is in precisely such areas that international committees such as the NEANDC and the INDC can fulfill their objective to promote cooperation in measurement and evaluation of nuclear data. To that end, these groups have agreed to develop a standing file covering the status of important standard reference data and discrepancies of major importance. It is the committee's hope that the compilation will stimulate additional measurements to resolve the discrepancies and improve the precision of the reference data.

The Status File is maintained jointly by the NEANDC and the INDC subcommittees on reference data and cross section discrepancies. To facilitate this approach it was agreed that continuing responsibility for individual reference standards and discrepancies entries should be assigned to subcommittee members so as to coincide where possible to the geographical or organizational assignment in the INDC subcommittees. Furthermore, in order to ensure the early availability to the sister committee, it was recommended that in the future each review be completed and available at the time of the meeting of the respective parent committee. Areas of non-overlapping responsibility may arise from time to time corresponding to changing initiatives and interests of the two committees. However, it is anticipated that such instances will constitute a minor portion of the respective data sets. Such cases can be regarded as the individual responsibility of the appropriate group.

II. Standard Reference Data

A. Discussion Summary

Committee agreed to develop the nucleus of a standard reference data set by completing short summaries according to assignments as follows:

1. (n,p) scattering cross section—Uttley (UK)
2. ^{3}He(n,p)—Jackson (US)
3. ^{6}Li(n,α)—Motz (US)
4. ^{10}B(n,α)—Wattecamps (BCMN)
5. Carbon, total and scattering—Smith(US)
6. ^{197}Au(n,γ)—Jackson (US)
7. ^{235}U(n,f)—Sowerby (UK)
8. $\overline{\nu}$ and fission spectrum for ^{252}Cf—Schmidt (IAEA)
9. Half life of ^{239}Pu—Vaninbroukx (BCMN)

These assignments are intended as the continuing responsibility of each individual for subsequent NEANDC meetings. An initial set of entries has been completed and is presented in the following section.

B. Data Set Entries

1. The H(n,n)H cross section

The cross section is used as a standard neutron scattering cross section relative to which other elastic cross sections are measured in the MeV region. It is also the primary cross section for neutron flux measurements above about 0.5 MeV and is used for this purpose in several ways which together require a knowledge of the angular distribution in both hemispheres. Detecting proton recoils from hydrogenous radiators involves the cross section at back C of M angles, while a common method of measuring the relative response of organic scintillators to neutron energy is to scatter an incident monoenergetic neutron beam from hydrogenous samples.

In the case of organic scintillators frequent use is also made of computer codes for calculating the neutron detection efficiency for different thresholds as a function of energy and in these calculations the differential scattering cross section is needed as input data.

Status

Until recently frequent use was made of the simple prescription by Gammel in which the angular distribution of scattering is symmetric about 90^{o}. The parameterization of all relevant n-p and p-p data in terms of phase shifts by Hopkins and Breit (Nuclear Data Tables A9, 137 (1971)) indicates a degree of anisotropy and asymmetry about 90^{o} in n-p scattering, even below 10 MeV, which is important in practical application. Recent angular distribution data confirm the Hopkins and Breit calculations and the recommendation that the evaluation based on these calculations by Stewart, LaBauve and Young (LA-4574) below 20 MeV should be adopted. This status report is concerned with recent developments in the total and differential n-p scattering cross sections below 30 MeV.

Accuracy of the total cross section

A more detailed tabulation of the recommended Hopkins and Breit calculations is given in the Los Alamos report LA-4574. The estimated standard deviation is ± 1% and is in agreement with the measurement of Davis and Barschall (PRC3, 1798 (1971)) between

1.5 MeV and 27.5 MeV. A recent evaluation of the effective range parameters by Lomon and Wilson [P.R. C9, 1329 (1974)] gives total cross sections which do not differ significantly from the Hopkins and Breit values in the MeV region. However a recent measurement of σ_T at 132 eV by Dilg [PR C11, 103 (1975)] results in effective range parameters which disagree significantly with the evaluation of Lomon and Wilson, but a measurement at 24 keV by Fujita et al [NFANDC(J)42L] agrees with the cross section based on the evaluated parameters. These disagreements of a fraction of a percent in the low energy total cross section are unlikely to materially affect the recommended values in the region of practical interest.

Accuracy of the differential scattering cross section

Until recently few measurements of the differential n-p scattering cross section have been made over an adequate angular range below 30 MeV with which to test the evaluation of Hopkins and Breit. Their evaluation was based on energy dependent phase shift analyses by the Yale [Phys. Rev. 165 (1968) 1579] and Livermore [Phys. Rev. 182 (1969) 1714] groups. The agreement between the two analyses as represented by Hopkins and Breit up to 30 MeV is better than 2% for $\sigma(0^o)$ and within 1% for $\sigma(180^o)$. The values of $\sigma(180) - \sigma(0)$ from 1 to 30 MeV vary by as much as 22%, however, and indicate the uncertainty on the p-wave phases, particularly $\delta(^1P_1)$, which determine the asymmetry in scattering at low energies. The uncertainty on $\delta(^1P_1)$ and its energy dependence has been stressed recently by Binstock [Phys. Rev. 10C (1974) 19] and by Voignier [Saclay Report CEA-R-4632 (1974)].

A single energy phase shift analysis of nucleon-nucleon scattering data near 50 MeV by Bryan and Binstock [Phys. Rev. 10D (1974) 10] illustrates the sensitivity of the value of $\delta(^1P_1)$ to the differential n-p scattering data included in the analysis. They point out the need for new and more precise differential n-p scattering data both at 50 MeV and in the energy range 20-30 MeV, especially at forward angles, so that better comparison can be made with model predictions of $\delta(^1P_1)$.

A measurement of the relative differential cross section by Burrows [Phys. Rev. 7C (1973) 1306] at 24 MeV over the (C of M) angular range 70^o to 160^o was normalized to the total cross section of

Hopkins and Breit. These data were included with those of Masterson [Phys. Rev. 6C (1972) 690], who measured the absolute cross section at 39° and 50.5° at the same energy, and they agree very closely with the Yale phase parameterization. More recently a measurement by Montgomery et al. [Annual Report UCD-CNL 186 (1975)] has been reported of the relative cross section at 25.8 MeV over a C of M angular range from 20° to almost 180° which also support the recommendations of Hopkins and Breit.

New data on the 180° cross section for n-p scattering around 24 MeV have been reported by Drosg (Conf. on the Int. of Neutrons with Nuclei, Univ. of Lowell, July 1976) who measured values $(5.7 \pm 3.3)\%$ lower than those calculated from the recommended Yale phase shifts but which agreed with those calculated from the Livermore unconstrained set. He also found that the ratio of the 180° cross section at 11.2 MeV to that at 25.3 MeV also agreed with the Livermore unconstrained set. These results have an important bearing on the accuracy of neutron flux measurements using proton recoil detectors. However the recent angular distribution data do not support the Livermore unconstrained phase shift analysis since it yields a value of $-1.85^\circ \pm 0.39^\circ$ for $\delta(^1P_1)$ at 25 MeV in contrast to $-4.90^\circ \pm 0.49^\circ$ for the Yale set and $-4.61^\circ \pm 0.08^\circ$ for the Livermore constrained set and results in an angular distribution more symmetric about 90° than is observed. The recent measurements between 20 and 30 MeV indicate that the coefficients of the second and third order polynomials, which determine the shape of the angular distribution between 30° and 150°, cannot be responsible for an error of $\sim 5\%$ in $\sigma(180)$ at 24 MeV. According to the fifth order representation by Hopkins and Breit of the differential cross section using the Yale phases, the respective contributions to $\sigma(180)$ from the second and third order terms are + 4% and + 5% while the summed contribution from the fourth and fifth order terms (both positive) is + 2%. Assuming zero contribution from partial waves $\ell > 2$, a reduction of 3% from the second and third order terms would have a marked effect on the angular distribution at intermediate angles. However a reduction in the third order term, representing mainly S-D interference, would have no effect on the recommendation by Lomon and Wilson [Phys. Rev. 9C (1974) 1329] for calculating $\sigma(180)$ up to 10 MeV. A reduction of up to 50% in the second order coefficient on the other hand, representing S-P interference, would increase the disagreement between their model predictions of $4\pi\sigma(180)/\sigma T$ and experimental values and increase the uncertainty on $\sigma(180)$ at 10 MeV to about 2%.

New measurements

The measurement at Harwell of the angular distribution of n-p scattering at 27.3 MeV over the C of M range 34^{o} to 116^{o} has been completed. In this experiment the scattered neutrons were detected and the data have been normalized to those of Burrows at the same energy in which the angular distribution between 71^{o} and 158^{o} was measured by detecting the recoil protons. The analysis is sufficiently far advanced to confirm the asymmetry in scattering about 90^{o} observed by the Wisconsin workers at 24 MeV and by the Davis group at 25.8 MeV.

Comments and recommendations

The discrepancy between a recent measurement of the 180^{o} cross sections above 10 MeV and the values derived from phase shift analyses should be investigated preferably by a method which is independent of another cross section. One method would be to measure the incident flux with a scintillator whose absolute efficiency has been calibrated by the associated particle technique, while another possibility may be to measure the cross section directly using the associated particle method with the $T(d,n)^{4}He$ reaction thus avoiding an independent flux measurement.

Since 1970 there have been several measurements of n-p scattering observables between 20 and 30 MeV which considerably improve the data set available to the Livermore group [Phys. Rev. 173 (1968) 1272] in their single energy phase shift analysis at 25 MeV. Another analysis at this energy, similar to the one carried out recently by Bryan and Binstock at 50 MeV, would be relevant to a better understanding of the n-p scattering cross section at lower energies.

C. A. Uttley.

Nuclear Physics Division,
Hangar 8.
AERE, Harwell.
8th November, 1976

2. $^{3}He(p,n)$

Description

This reaction is widely used as a neutron flux monitor in the thermal and < 10 eV neutron energy region. A convenient detection reaction in gas proportional counters when high efficiency is not a primary consideration.

Status

No evidence has been found for any measurements or applications of this reaction above thermal in the last several years. For a status review of earlier measurements see Paulsen and Liskien, EANDC(E) 153L (1972).

Comments and recommendations

The use of this cross-section as a flux standard has been proposed on numerous occasions. However, difficulties in technical implementation have precluded its use above the near thermal region. Despite numerous inquiries there is no evidence for any but incidental use as a flux standard. The standard subcommittee of the INDC recently concluded that "lack of interest over such an extended period is certainly due to the non-existence of suitable detector systems and reduced emphasis should be given to this standard." However we recommend that the planned removal of the $^{3}He(n,p)$ cross section from the reference data be deferred in view of the promising new work on a liquid ^{3}He detector currently in progress at Bochum, Germany under the direction of Dr. Zeitnitz.

H. E. Jackson
September 1976

3. ^{6}Li(n,α)

Because of its relatively high cross section and Q-value and the convenience of counting the light triton and alpha products, this reaction is widely used as a standard. In recent years a commercially available scintillating glass which contains a small amount of ^{6}Li has found wide use. Work is now underway to characterize and standardize this material. Lithium is also envisaged as a tritium breeding medium in most fusion designs.

Status

The R-matrix analysis upon which the ENDF/B Version V standard # is based includes recent LASL measurements of t-α differential cross sections[1] and analyzing powers,[2] as well as new measurements of the total cross section of Harvey[3] (ORNL) and of relative (n,α) cross sections of Lamaze (NBS).[4] Some of the LASL data[1,2] which are yet to be changed significantly due to multiple scattering corrections, were essentially weighted out of the fits. The Table summarizes the input data sources.

The R-matrix analysis gives a peak (n,α) cross section of ~ 3.3 b at 240 keV and a peak total of 11.26 b at 245 keV. The 5-keV difference between the peak cross sections of the total and (n,α), as predicted in the analysis, agrees closely with the measurements of Harvey[3] and of Lamaze,[4] without shifting either energy scale in their input data. The cross sections predicted at the peak, however, are ~ 2% and 3% higher, respectively, than the experiments indicate. At energies below 200 keV, the agreement of the calculated (n,α) with Lamaze's data is generally better than 2%, and the agreement of σ_T with Harvey's data is generally better than 1%, except for a region around 150 keV, where the difference is ~ 5%.

New measurements

Knitter has made energy resolution corrections to σ_T,[5] and has extended measurements of $\sigma_{n,n}$ down to 100 keV.[6] The new $\sigma_{n,n}$ data are higher in the peak of the resonance than earlier values of Lane, in agreement with the Version V results. Knitter's resolution-corrected value of the peak total cross section[6] is now 11.20 ± 0.08 b, as compared with Harvey's value of 11.0 ± 0.06 b. A 6-keV difference (Knitter-Harvey) in the position of the peak persists.

A new measurement of $\sigma_{n,t}(0^{o})$ and $\sigma_{n,t}(180^{o})$ from the $T(\alpha, {}^{6}Li)n$ inverse by Brown, et al.[7] at LASL confirms a peak position of 240 keV, and agrees in scale with the Version V predictions near the peak (see Fig.).

Measurements of ${}^{6}Li(n,\alpha){}^{3}H$ anisotropy from 0.5 eV to 25 keV have recently been reported by Raman, et al.[8] but the tabular data are not yet available for input.

Conclusions and recommendations

Although the LASL R-matrix analysis of the ${}^{7}Li$ system indicates relatively good agreement with the most recent measurements of the total, (n,α), and the elastic scattering cross sections, discrepancies among the earlier results are still not understood. Following the September 1976 NEANDC meeting, Fort has outlined corrections to his (n,α) data,[9] which would produce a correction factor of 1.117 over the energy range of his measurements.* These "corrected" Fort values have not been used as input. It is readily apparent that Fort's corrected peak cross section is in much better agreement with this R-matrix analysis but checks must be made in the wings of the resonance. Recent ${}^{6}Li(n,\alpha)$/ ${}^{235}U(n,f)$ data from Harwell will be issued as a report (AERE-R 8556).[10]

The results of this R-matrix analysis are available through CSEWG as the ENDF/B File, Version V, and are shown in the figures. For convenience of the experimentalists, the center-of-mass angular distributions of the emitted tritons are included in the file.

Further work in understanding the detailed response of lithium-loaded glass scintillators would be valuable. A limited sample set has been measured for lithium content, but scintillation properties over the surface have not yet been reported.

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*This is a slightly altered value from the one distributed at the 19th NEANDC meeting, which was 1.114. This correction relates to the ${}^{6}Li$ content weighted over the appropriate beam distribution and measured lithium content. See "The Measurements of the ${}^{6}Li$ Content of Li Loaded Glass Scintillators" by M. C. Moxon, et al., AERE-R-8409, to be published.

TABLE

The $^6Li(n,\alpha)T$ Cross Section Below 1 MeV

ENDF/B Version V

The following experimental data were used as input to the R-matrix analysis using the multilevel, multichannel code EDA.

	Channel	$\sigma(E_n)$	$\sigma(\theta)$	$P(\theta)$	Ratio
A.	Total	*Harvey[3] *Diment			
B.	Elastic $(n+^6Li)$	Knitter[a]	Knitter[a] Lane[b]	Lane	
C.	$n+^6Li \rightarrow t+\alpha$	Meadows[c] Poenitz[d] *Lamaze[4]	Overley Schroder[f]		Sowerby[e]
D.	Elastic $(t+\alpha)$		Jarmie[1]	Hardekopf[2]	

[a]Knitter, private communication.

[b]Shape only.

[c]Thermal value.

[d]Poenitz' data above 600 keV.

[e]Sowerby's $^6Li/^{10}B$ ratio data up to 1 keV.

[f]Asymmetry at 25 keV.

*Energy Scale Fixed.

REFERENCES

[#]A report "n + ^{6}Li R-Matrix Analysis Results" by G. Hale, L. Stewart, and P. G. Young, to be published.

[1]N. Jarmie, et al. "Elastic Scattering of 7-12 MeV Tritons by Alpha Particles," Bull. Am. Phys. Soc. 20, 85 (1975); and private communication.

[2a]R. A. Hardekopf, et al. "Analyzing Power for ^{4}He(t,t)^{4}He Elastic Scattering," Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions, Zürich, 1975. Edited by W. Gruebler and V. König (Birkhäuser, Basel, Switzerland, 1976) p. 579.

[2b]R. A. Hardekopf, et al. "Calibration of a Polarized Triton Beam," ibid., p. 903.

[3]J. A. Harvey and N. W. Hill, "Neutron Total Cross Section of ^{6}Li from 10 eV to 10 MeV," Proceedings of a Conference on Nuclear Cross Sections and Technology, March 3-7, 1975, Washington, D. C. Edited by R. A. Schrack and C. D. Bowman. NBS Special Publication 425, p. 244.

[4]G. P. Lamaze, et al. "A New Measurement of the ^{6}Li(n,α)T Cross Section from 3 to 600 keV," Proceedings of the 1976 International Conference on the Interactions of Neutrons with Nuclei, July 6-9, Lowell, MA, Paper PB1/F3, to be published.

[5]Knitter, private communication, December 1975 and EUR-345e (1967).

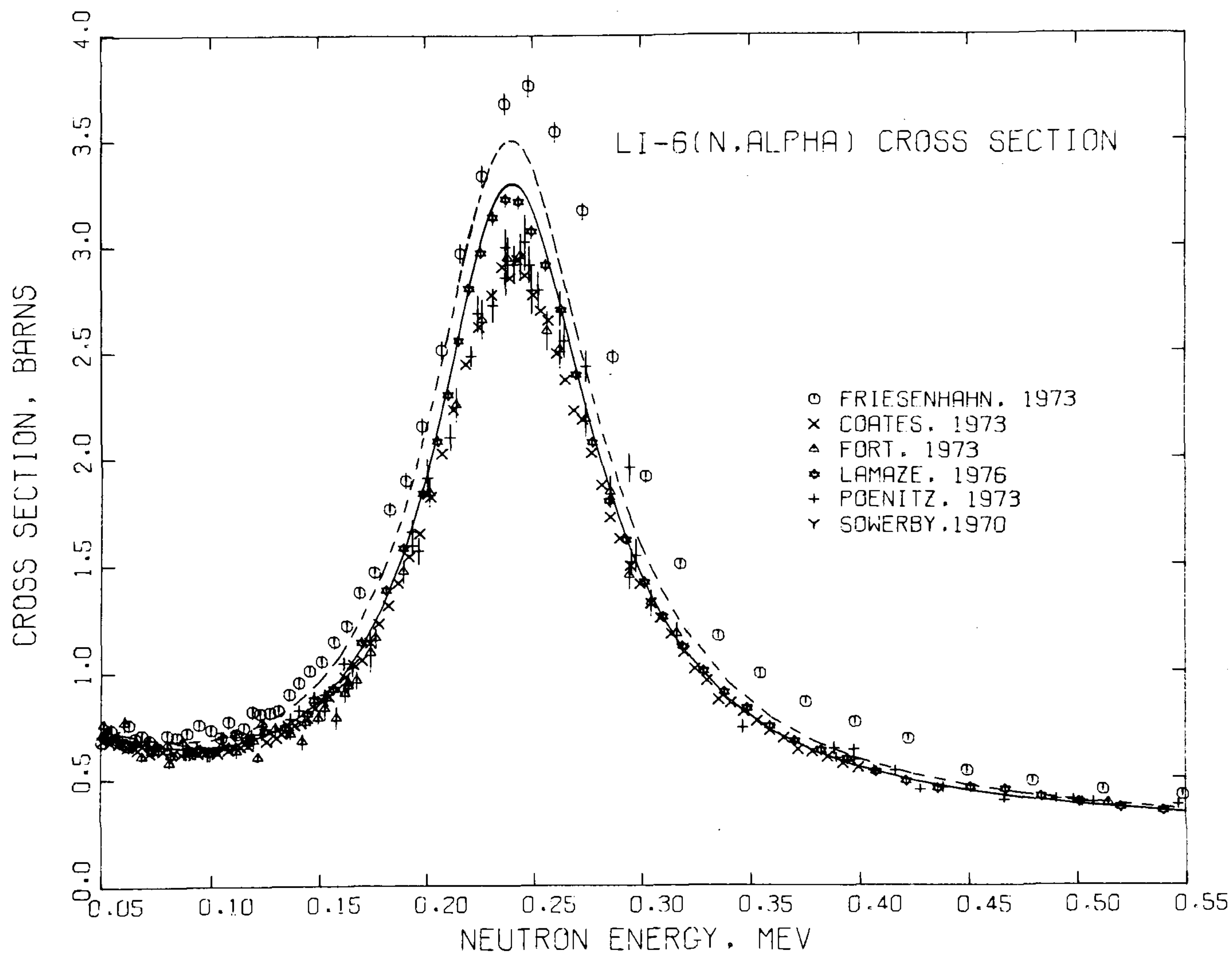
[6]H.-H. Knitter and C. Budtz-Jørgensen, "Measurements of Neutron Total and Scattering Cross Sections of 6-Li," Proceedings of the 1976 International Conference on the Interactions of Neutrons with Nuclei, July 6-9, Lowell, MA. Paper PG2/I5, to be published.

[7]R. E. Brown, et al. ^{3}H(α,^{6}Li)n Reaction at 0°, to be published.

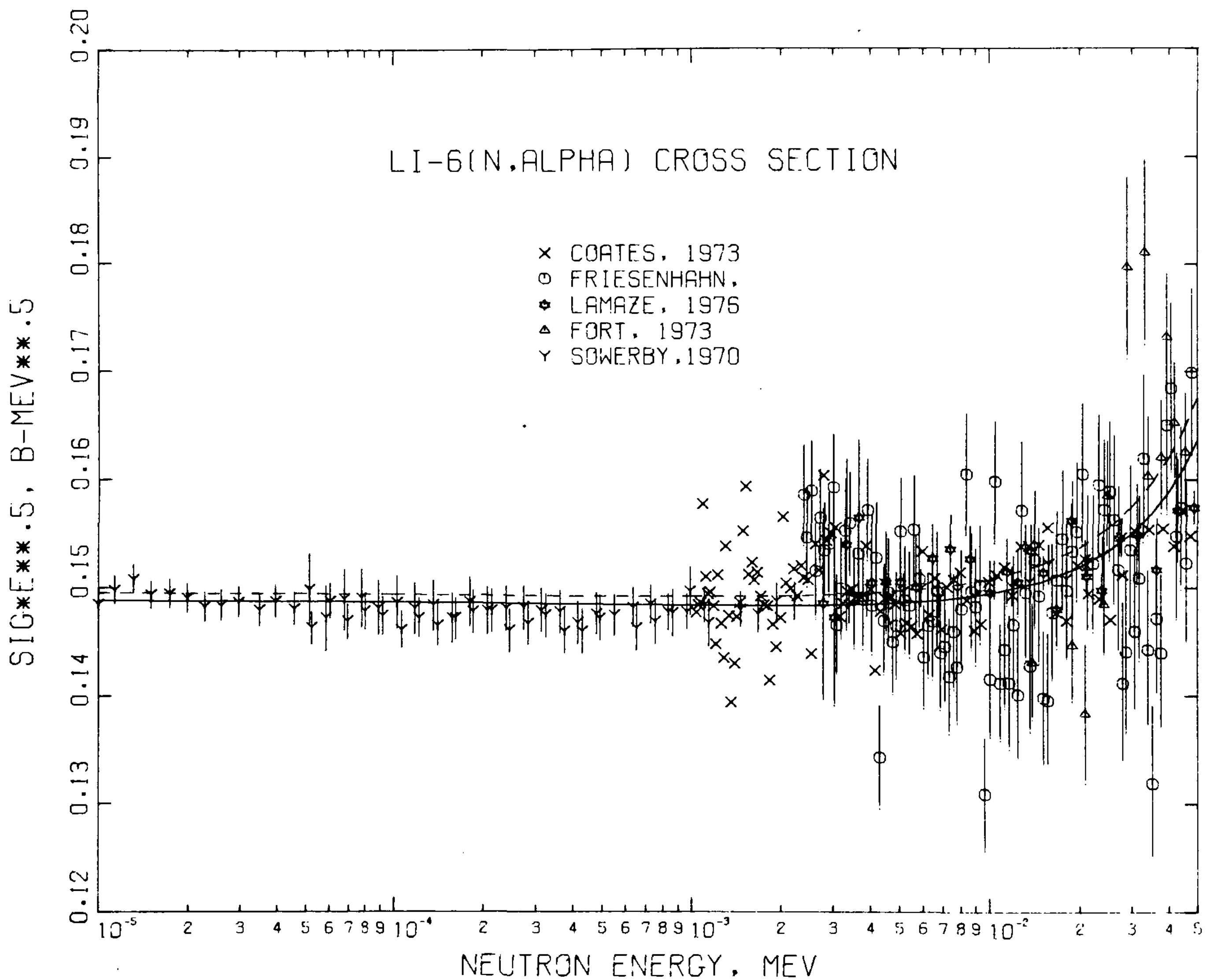
[8]S. Raman, et al. "Angular Anisotropy in the ^{6}Li(n,α)^{3}H Reaction in the eV and keV Energy Region," ibid., Paper PB1/F2.

[9]E. Fort, Private Communication to H. Motz, dated Oct. 19, 1976.

[10]D. B. Gayther, Private Communications to H. Motz, dated Oct. 18, 1976 and Dec. 3, 1976



Recent R-matrix results (solid line, Version V) obtained from simultaneous least squares fits with other data sets compared to ENDF/B-IV (dashed line). See Table for data sets used as input. (The Fort data plotted here were not corrected as mentioned in the text.)



Recent R-matrix results (solid line, Version V) obtained from simultaneous least squares fits with other data sets compared to ENDF/B-IV (dashed line). See Table for data sets used as input. (The Fort data plotted here were <u>not</u> corrected as mentioned in the text.)

4. $B^{10}(n,\alpha)$

Description

Natural boron or ^{10}B enriched samples are often used for neutron flux determination. A large variety of detectors is used, and the reaction underlying the detection systems is either

$$^{10}B(n,\alpha_1\gamma)^7Li \quad \text{or} \quad ^{10}B(n,\alpha_o + \alpha_1\gamma)^7Li.$$

α_o refers to α emission leaving the residual nucleus ^7Li in the ground state, α_1 refers to α emission leaving the residual ^7Li nucleus in its first excited state which decays by prompt emission of a 478.5 keV gamma ray. The Q value of the reaction is 2.8 MeV.

Status

From thermal energy up to 10 keV the cross-sections $\sigma(n,\alpha_1)$, $\sigma(n,\alpha_o)$ and $\sigma(n,\alpha_o + \alpha_1)$ are known with the required accuracy. From 10 keV to 1 MeV an accuracy of 2% is requested by eleven priority one requests in WRENDA 76-77. There is no single other cross-section requested so unanimously with this urgency. Furthermore, by comparing the total number of requests expressed for a single cross-section, $^{10}B(n,\alpha)^7Li$ appears on third position immediately after ^{235}U fission and ^{238}U capture. The most recent evaluation was done in the frame of ENDF/B IV by G. M. HALE, R. A. NICLEY and P. G. YOUNG [NEANDC (U) 196/L] and the latest data taken into account are those of S. J. FRIESHENHAHN et al. and G. P. LAMAZE et al. of July 1974. Since then other measurements and interpretations have been performed:

(1) The $^{10}B(n,\alpha_1)^7Li$ cross-section from 5 to 600 keV, by R. A. Schrack, G. P. Lamaze, O. A. Wasson and A. D. Carlson Proc. Int. Conf. Inter. Neutrons with Nuclei, Lowell, July 1976

(2) $^{10}B(n,\alpha)^7Li^*$ differential cross-section measurements between 0.2 and 1.25 MeV, by R. M. Sealock and J. C. Overley, Phys. Rev. C. Vol. 13 No. 6, June 76, p. 2149.

(3) R-matrix analysis of the light element standards, by G. M. Hale, NBS SP 425, Proc. of a Conf. Washington, March, 1975.

(4) MeV neutron total cross-section of ^{9}Be, $^{10,11}B$ and $^{12,13}C$, by G. F. Auchampaugh, S. Plattard, R. Extermann and C. E. Ragan III. Proc. of an Int. Conf. Interactions of Neutrons with Nuclei, Lowell, July 1976.

(5) A new measurement of the $^{6}Li(n,\alpha)$ T cross-section from 3 to 600 keV, by G. P. Lamaze, O. A. Wasson, R. A. Schrack and A. D. Carlson, Proc. of an Int. Conf. Interactions of Neutrons with Nuclei, Lowell, July, 1976.

(6) Neutron standards and their application, by H. Liskien, Proc. of an Int. Conf. Interactions of Neutrons with Nuclei, Lowell, July 1976.

(7) Recommended ^{10}B neutron cross-section data have been accepted for ENDF/B versionV standards but were by the time of this writing not yet available to the author.

The data of $\sigma(n,\alpha_1)$ obtained by R. A. Schrack lie between the previous extremes and are well fit by an R-matrix analysis. The ^{10}B differential cross-section measurements by R. M. Sealock and J. C. Overley are of particular interest because of three reasons:

- very selective detection system delivering the energies of the neutron and of the α particles,
- the angular distribution of the (n,α_1) reaction is measured to be an-isotropic in particular at about 400 keV,
- data for (n,α_o) do not agree well with previous data around 300 keV.

The R-matrix calculations by G. M. Hale show that these calculations are well suited for obtaining smoothed representations of standard cross-sections for light elements but more accurate input data are still needed; for instance angular distributions at 150 keV.

Quantitative results of G. F. Auchampaugh et al. of σ_{tot} measurements are not available yet because of a sample thickness problem but data are expected in the next few months.

The measurement of $^{6}Li(n,\alpha)T$ of G. P. Lamaze et al. is of particular interest since it is useful for a cross check of the widely used $^{10}B(n,\alpha)^{7}Li$ evaluation of Sowerby which relies in fact on a measured $\sigma(n,\alpha)$ ratio of ^{6}Li to ^{10}B and a measured σ_{tot} of ^{6}Li.

The review paper of H. Liskien has indicated that many (n,α) data show the same shape in the energy range 0.1 to 1 MeV though they strongly differ in absolute value.

Comments and recommendations

The data made available very recently indicate a need for further updating of evaluations, and the new ENDF/B V version, which is expected to be published soon, might well improve the reliability of present recommended data. Nevertheless, we expect that the ENDF/B V evaluation will illustrate the need for better experimental data between 30 keV and 100 keV for real improvement of the reliability of the standard, and from 100 keV to 1 MeV also to get enough overlap with the ^{235}U fission and H(n,n)H elastic scattering standards.

E. Wattecamps
15.11.1976

5. Carbon Total and Scattering Cross Sections

Justification and use

Used for verification and reference standard (< 5.0 MeV) in fast-neutron-scattering studies and as an energy-scale standard in both white and monoenergetic source measurements.[1] Both differential and angle-integrated ($\equiv \sigma T$) elastic cross sections are of interest in the relatively energy-smooth regions (e.g. 2.1—2.8 MeV). For $E_n < 15$ MeV several isolated and sharp resonances are available for energy reference (e.g. 2.08-MeV resonance). Finally many n-p standards are employed as a hydrocarbon and thus the carbon cross sections are of interest.

Status and recent results

There have been a large number of determinations of the total cross section.[2] The more recent and comprehensive are those of Refs. 3—7 obtained with varying techniques. Below ≈ 1.5 the results of Refs. 3, 5 and 8 agree in magnitude to within ≤ 2%. Above 1.5 MeV results of Refs. 5 and 7 are consistent to ≈ 2% to 5.0 MeV. Results of Ref. 4 are larger than the above by 5—8% from ≈ 0.5 to 5.0 MeV. Thus select recent and comprehensive σT values seem to give the total cross section to 5 MeV with ≤ 2% uncertainty. This estimate applies only to wide regions of relatively smooth energy dependence.

Total cross-section energy scales at the sharp 2.08-MeV resonance as given in Ref. 5, 7 and 9 and discussed in Ref. 5 are consistent to ≈ 1 keV. This is a very good energy calibration point. At other and higher energies discrepancies between measured and evaluated sets can be 5—10%.[6] There are a number of resonances to 15 MeV that could be useful calibration points. Only the 2.08 appears suitably known.

Differential elastic scattering cross sections for $E_n < 1.5$ MeV are generally consistent to 10% and, collectively, probably have the potential for an evaluated accuracy of probably 5%.[11, 12, 14] Above 1.5 to 4.0 MeV recent detailed measurements provide accuracies of 5—10% at intervals of ≤ 100 keV.[7] Additional measurements of Ref. 13 carry the differential cross sections to the upper energy of magnitude reference–standard interval of ≈5.0 with less definition but good accuracy.

The n + C^{12} system is reasonably defined[15] and resonance interpretation can interpolate between measured values. Such interpretations have been pursued on several occasions, most recently by Holt et al.[7] The latter work achieved a good consistency between measured total cross sections of Refs. 3, 5 and 7, the differential elastic distributions of Refs. 7, 10—13, the thermal cross section[16] and the measured scattered neutron polarizations.[17] The interpretation and consequent evaluation could certainly be improved by more careful evaluation of experimental results. However, it already indicates the unsuitability of some measured total cross-section values.

Conclusions and recommendations

1. Current experimental knowledge of the total cross section to 5 MeV should be used to generate a comprehensive data set.

2. Differential elastic cross sections should be assembled over a similar energy range.

3. Using resonance theory 1) and 2) above should be evaluated with consistent σ_{tot}, $d\sigma/d\Omega$, Pol. and thermal results. It is expected that the resulting uncertainty estimates for σ_{tot} will be ≤ 2.0% and of $d\sigma/d\Omega$ ≤ 5%, in which case no further measurements of precision magnitudes are at present warranted. Should these uncertainty estimates not be met, the analysis should indicate where error estimates are warranted. The concept is based upon use of these cross sections as magnitude references in regions of smooth energy dependence not appreciably affected by exact knowledge of resonance energies.

4. The energy scale is precisely known only for the 2.08-MeV resonance. Measurements should be pursued to ascertain the energies of selected sharp resonances to at least 5 keV to 10—15 MeV.

Both white-source and monoenergetic-source techniques should be used. Only with success will carbon be a good energy reference over a wide MeV energy range. Such is desirable as it is an easily used and simply understood material.

The above involve both analytical-theoretical and experimental techniques. It is suggested that they be attacked by a selected working group consisting of such talent assembled under NEANDC auspices. Problem area 4) above is already being approached in that manner.

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A. B. Smith (U. S.)

6. ^{197}Au(n,γ)

Description

Availability of thin foils of high chemical purity, simplicity of disintegration scheme of neutron induced activity, appropriately short half life and ease with which induced activity can be monitored insure the continued widespread use of this reaction as a neutron fluence monitor.

Status

The major issue in the capture cross section for ^{197}Au is an apparent difference between activation and non-activation results over the energy range 0.1 to 2.5 MeV amounting to as much as 5 to 8 percent. However, there is a very strong correlation with time, the most recent measurements giving very much better agreement than the complete body of available data. In addition, there was a strong suggestion in the earlier analysis that part of the difficulty arises from failure to account for the different reference standards used in the various experiments. The most recent results using the two techniques are consistent to within their errors ~ 2.5%. A new evaluation has been completed by CSWEG for ENDF/B-V and final approval is pending. The evaluation differs from earlier efforts in that all input data were renormalized to an approved set of primary standards to give a consistent set of standard cross sections, (n,p) ^{6}Li(n,α), ^{10}B(n,α), ^{197}Au(n,γ) and ^{235}U(n,f). The new evaluated data set is based on measurements of Macklin, et al.[1], Fort and Le Rigoleur,[2] Poenitz,[3] and Lindner, et al.[4] in the energy range 100-1000 keV, and above 1000 keV on the work of Poenitz and Lindner, et al. The result is to decrease the capture cross section by about 4%, over earlier estimates, about the magnitude in the uncertainty. The following observations are made relative to the data base considered:

(1) data of Macklin, et al., Lindner, et al., and Le Rigoleur are generally in very good agreement.

(2) as shown by Fort and Le Rigoleur the activation and non-activation measurements are in reasonable agreement with each other particularly in the energy region 400-500 keV where the deviation is only about 2%.

(3) data of Paulsen, et al.,[5] Fricke, et al.,[6] and Barry, et al.,[7] measured relative to the (n,p) cross section are consistently high with respect to the ENDF/B-IV evaluation and with the data of Macklin, et al., Lindner, et al., Poenitz, and Fort and Le Rigoleur. This may have to do with response of the hydrogen proportional counter.

(4) in the energy range 1000-3500 keV, the data of Paulsen, et al., appears to converge, particularl at the high energy end, with that of Poenitz and Lindner, et al.

(5) the Robertson, et al.,[8] cross section value of 966 keV is about 12% high with respect to Poenitz, Lindner, et al., and ENDF/B-IV evaluation but somehow in agreement with the data point of Paulsen, et al. Since it is believed that there is no structure in the gold capture cross section at this energy, the result of Robertson, et al., was down-graded.

(6) the apparent structure in Macklin, et al.'s renormalized data at about 250 keV is partially due to a lack of a precise knowledge of the peak position of the resonance at about this energy.

(7) the data of Czirr and Stelts[9] is high when compared with other data, and with the ENDF/B-IV evaluation. It is to be noted that the data points at 319, 412, and 532 keV were withdrawn by the authors.

<u>Comments and recommendations</u>

In application of this reaction in the ≤ 100 keV region due consideration must be given to the energy spectrum of the incident flux. Complexity of the resonance structure probably preclude consideration of Au (n,γ) as a primary reference standard in this region. In the region from 100 keV - 3500 keV the capture cross section of gold is a wide-used primary standard with a current uncertainty of about ± 4%. The remaining problems appear to involve the alternate standards used in measurements which are discrepent with the "accepted" cross section. The following recommendations have been made: The datum of Robertson, et al.[8] requires further confirmation. The high data points of Paulsen, et al.[5] should be clarified. (n,p) scattering was the reference standard in this work.

For a more detailed discussion together with a <u>preliminary</u> evaluated data set the reader is referred to BNL-NCS-21774, an informal report by S. F. Mughabghab from which much of the above material has been drawn.

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H. E. Jackson (U.S.)

7. U-235(n,f)

Description

The U-235 fission cross-section is a good standard because

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

(b) U-235 has a long half life so that α pile up and handling problems are minimised

(c) the cross section is of reasonable magnitude at all energies of interest

(d) U-235 is readily obtainable

When U-235 was initially selected as a standard it was anticipated that there would be no fine structure in the cross-section above 10 keV. This is now known to be incorrect and care must, therefore, be taken in using the cross-section as a standard below 200-300 keV where structure has been observed.

Status

The information on the U-235 fission cross-section was reviewed in June 1976 by the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-sections of U-233, U-235, U-238 and Pu-239. As a supplement to the proceedings* of this meeting there is a comprehensive summary of the available data including graphical comparisons of the various measurements and the table lists the experiments on the absolute measurements on U-235 which were considered.

The Specialist Meeting concluded that between 0.01 MeV and ~ 15 MeV the data are consistent with an evaluation known to ± 3% (± 1σ) except in the range 0.25 to 0.4 MeV where there is a local discrepancy which limits the accuracy to ± 5%. Above 15 MeV the situation is much worse as the data appear to divide into a high group and a low group which are up to ~ 15% apart.

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*Proceedings of the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-Sections of U-233, U-235, U-238 and Pu-239. ANL-76-90, NEANDC(US)-199L, ERDA-NDC-5/L To be published.

Comments and recommendations

The present accuracy of ± 3% between 0.1 and 15 MeV (neglecting the small region 0.25 - 0.4 MeV) meets the least stringent requirements specified in WRENDA-75 but does not meet the ± 1 to 2% requests specified by many countries. There is obviously a need to resolve the local discrepancy between 0.25 and 0.4 MeV but the more difficult and general objective is to realise accuracies of ± 2% over the whole energy range. In order to achieve these higher accuracies it is necessary to

(1) make individual measurements more precise by improving and reducing the corrections which must be applied to the raw data,

(2) improve the documentation of experiments as a high accuracy can only be justified if there is excellent documentation,

(3) use a variety of techniques and detectors. The importance of spot point data should not be forgotten at a time when many measurements are being made with "white spectrum" neutron sources.

WRENDA-75 only includes one request above 15 MeV but it is obviously important to solve the discrepancies in this energy range as these may be due to effects which could influence the data at lower energies.

M. G. Sowerby

U-235 fission cross-section measurements considered by the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-sections of U-233, U-235, U-238 and Pu-239

Set	Name	Reference	Source/Status	Comments
1	Gwin	ANS 15, 481	CSISRS	
2	Grundl	76 ANL	CSISRS	Av. over Cf spectrum
3	Gilliam + R	76 ANL	PC	New values
4	Poenitz	NSE 53, 370	CSISRS	
5	Hansen	76 ANL	CSISRS	
6	Czirr + S	NSE 57, 18	CSISRS	Shape only
7	Czirr	UCRL-77377	CSISRS	Rel. Li-6, new values
8	Kaeppelar	7 Vienna	CSISRS	Also ANL 70
9	Gayther	75 Wash	CSISRS	Shape only
10	Cance	76 ANL	CCDN	
11	Gorlove	AE6, 453	CSISRS	
12	Chelnokov	AE 31, 103	CSISRS	
13	Kuks	73 Kiev	CSISRS	
14	Smith	BAP 2, 196	CSISRS	
15	Henkel-LE	LA-2122	CSISRS	
16	Poenitz 68W	68 Wash	CSISRS	
17	Melkonian	NSE 3, 435	CSISRS	
18	Yeater	PR 104, 479	CSISRS	
19	Diven PR	PR 105, 1350	CSISRS	
20	Williams	LA-150	CSISRS	
21	Nyer	LAMS-938	CSISRS	
22	Whal	LA-1681	CSISRS	
23	Moat	JNE 16, 270	CSISRS	
24	Adams	JNE 14, 85	CSISRS	Shape only
25	White	JNE 19, 325	CSISRS	
26	Perkin	JN 19, 425	CSISRS	Sb-Be source
27	Knoll + P	JNE 21, 643	CSISRS	
28	Netter	CEA-1913	CSISRS	
29	Allen	PPS/A70, 573	CSISRS	
31	Pankratov	AE, JNE 16, 494	CSISRS	Several sets
34	Goldanski	DOK 101, 1027	CSISRS/HOLD	Energies unclear
35	Szabo	76 ANL	CSISRS, CCDN	Several sets, latest values
36	Blons	NSE 51, 130	CSISRS, BHAT	
37	Hall	LA-128	PAPER	
38	Adamov	75 Kiev	PAPER	Av. Cf spectra
39	Benedict		NOT YET	
40	Van Shi-Di	65 Salzburg	BHAT	Requested from NNCSC
42	Dorofeev	JNE 5, 217	PAPER	
43	Lemley	NSE 43, 281	BHAT	
44	Wagemans	ANE, t.b.p.	CCDN	New data
45	Michaudon		BHAT	Some values missing
46	Perez	NSE 55, 203	BHAT	Some values missing
47	Wasson	76 ANL	PC	New data
48	DeSaussure	ORNL-1804	BHAT	
49	Ryabov	INDC-31/U	BHAT	
50	Taschek	LA-445	PAPER	
51	Bowman	66 Wash	BHAT	
52	Schomberg	JNE 24, 269	PAPER	
53	Bailey	LA 447	PAPER	
54	Deruytter		BHAT	
55	Shore	PR 112, 191	BHAT	
56	Cierjacks	76 ANL	PC	Relative H(n,n)
57	Brooks	66 San Diego	NOT YET	
58	Zhuravlev	76 Lowell		

8. $\bar{\nu}_p$ and N(E) of ^{252}Cf

Description

$\bar{\nu}_p$ = prompt number of neutrons emitted in spontaneous fission of ^{252}Cf, used as basic standard for almost all $\bar{\nu}$ measurement. N(E) = spectrum of prompt neutrons from spontaneous fission of ^{252}Cf, besides N(E) for thermal neutron fission of ^{235}U used as standard fission spectrum.

Status and recommendations

$\bar{\nu}_p$ - After the last INDC review in October 1974 the present knowledge of microscopic ν_p data is summarised in the review paper given by H. D. Lemmel from the IAEA Nuclear Data Section at the Washington Conference (paper No. EA-2). The previous discrepancy essentially between Mn-bath and liquid scintillator measurements has practically disappeared, partly because revisions have brought previous extreme values together within experimental accuracy, partly as a result of the recent very careful liquid scintillator remeasurement of Boldeman from Lucas Heights, which gave a lower value than the previous liquid scintillator measurements. At present, five of the nine available values for $\bar{\nu}_p$ are in excellent agreement in the range between 3.715 and 3.735 including the three most recent and most accurate determinations by De Volpi, Axton, and Boldeman. The present weighted mean of all results is

$$\bar{\nu}_p\,(^{252}\text{Cf}) = 3.731 \pm 0.008$$

Regarding microscopic measurements, only minor work seems still to be needed as follows. In the calculation of the above weighted average the rather low Harwell boron pile results were slightly down-weighted due to neutron absorption by carbon and copper, effects which had been neglected in previous analyses. Improved Monte-Carlo calculations would be desirable for a still outstanding quantitative assessment of this effect. Secondly, according to new Monte-Carlo simulations by Poitou and Signarbieux the impact of emission of gamma ray cascades and their interaction with the scintillator which led to a 0.4% reduction of Diven's 1963 result, should be assessed also for the other previous liquid scintillator measurements.

However, the discrepancy of about 1% between the Mn bath results of De Volpi and Axton ($\bar{\nu}_p = 3.725$) and the ^{252}Cf $\bar{\nu}$ values derived from MTR η measurements and $\bar{\nu}/\bar{\nu}_{Cf}$ ratios (average derived $\bar{\nu}_p = 3.776$ in the careful investigations of J. R. Smith from Aerojet Nuclear Company, Idaho, reported at the Washington Conference (paper No. DB-9) still persists (supposedly well known, the changes from the 1969 to the 1974 IAEA evaluation are very minimal). In a careful study comprising 1) the calibration of a ^{252}Cf source previously calibrated by De Volpi in the MTR Mn bath, 2) examination of De Volpi's recommendations for altering the MTR η values and 3) examination of the results of Monte Carlo calculations of the MTR experiment carried out at Bettis Atomic Power Laboratory, Smith found only very minor modifications to be applied to the MTR η values.

For the moment it seems advisable to wait for the results of tank calibration of ^{252}Cf $\bar{\nu}$ performed by Spencer et al. from Oak Ridge (see status report in USNDC-75) during 1975 before issuing any further recommendations, e.g. to perform new η measurements.

Status

N(E) - Since the INDC meeting in October 1974 no new final data on N(E) of ^{252}Cf have become available. New results are currently being expected from Lucas Heights.

Grundl and Eisenhower from the National Bureau of Standards (see Washington Conference, paper no. DB-6) recently performed a Maxwellian shape fitting of all published measurements of N(E) for ^{252}Cf in the energy range, where the available data are more reliable, 0.25—8 MeV, excluding thereby about 6% of the spectrum where the data are less confident. The reference Maxwellian shapes differ from the final evaluated shape by $\leq 2\%$ over the energy range 0.25—8 MeV. The authors derived a weighted average energy of 2.13 ± 0.027 MeV; this is in fairly good agreement with the value given by Lemmel at the Washington Conference, i.e. 2.19 ± 0.08 MeV, within the error limits quoted by him. Grundl and Eisenhower checked the reliability of their $\bar{E}$ value by comparing observed and computed spectrum sensitive integral quantities such as the age-to-indium-resonance in light water and the fission spectrum averaged fission cross-section of ^{238}U. The results are satisfactory as the following table shows.

	Age in light water (cm^2)	(^{238}U) (b)
Observed	28.7 ± 0.4	0.320 ± 0.008
Computed	27.7 ± 0.4	0.313 ± 0.003
Observed / Computed	1.05 ± 0.025	1.023 ± 0.03

Recommendation

N(E) - The ongoing measurements of N(E) for ^{252}Cf may lead to a better definition of the spectrum below 0.25 and also above 8 MeV where deviations from a Maxwellian shape can be expected. A re-evaluation over the total energy range is recommended after the final results from the ongoing measurements have become available.

J. Schmidt (IAEA)
September, 1976

9. Half-Life of ^{239}Pu

Application

The half-life of ^{239}Pu is important for several reasons. For example, it plays an important role in the evaluation of fission constants since it can influence the final evaluated values of these constants. Furthermore, an accurate knowledge of the half-life is needed for the accurate mass determination of ^{239}Pu samples using α-counting techniques.

Status and recent results

The values reported up to July 1975 were given in the 1975-status report (CBNM/RN/11/75). Recently two new preliminary values, reported by Jaffey et al., became available. All values reported since 1971, and presented in Table 1, are in good agreement. The last four values are still preliminary ones.

Table 1. Half-life values of ^{239}Pu

Reference	Author	Year	Method	Result in years
1	Oetting	1971	calorimetry	24065 ± 50
2	Aleksandrov	1975	specific activity by α-counting	24060 ± 38
3	Glover	1975	"	24115 ± 80
4	Vaninbroukx	1975	"	24173 ± 100 (97.3% conf. level)
5	Jaffey	1976	"	24130 ± 16
5	Jaffey	1976	MS determ. of ^{235}U grown into ^{239}Pu	24143 ± 10

The arithmetic mean of the 6 values is:

(24114 ± 44) yr

where the uncertainty quoted is the standard deviation.

Conclusions and recommendations

1. The convergence of the results reported since 1971 and obtained by different methods suggests that very probably a reliable value for this half-life can be recommended in the near future.

2. Since most of the values are preliminary ones, and since in most cases the uncertainties quoted are not well specified (random and systematic uncertainties, confidence level) the use of the following value is suggested, until the final values of the measurements in progress are available:

$$T_{1/2} - {}^{239}Pu = (2.411 \pm 0.010) \times 10^4 yr$$

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R. Vaninbroukx
(BCMN)

III. NEANDC-INDC Discrepancy File

A. Introduction

The list of nuclear data discrepancies which follows represents a selection by the NEANDC and INDC of nuclear cross sections or related data which have been measured directly in several laboratories with conflicting results. Those cases have been included for which resolution of the experimental discrepancy will have a major impact on current understanding or design of nuclear fission or fusion energy systems. The list should be constructed as a working document with the status comments changing as new measurements and evaluations become available. Responsibility for maintenance has been assigned to individuals on such a basis with the understanding that monitoring of the status of specific entries is a continuing obligation.

The entries included in this report do not constitute a final discrepancy file. Several cases require continuing surveys and analysis of experimental data. These efforts are in progress and the files will be updated as they become available. The specific assignments for maintenance of individual entries are given below. As emphasized earlier, these are to be understood as obligations on the part of the organization which the individual represents. In this way it is hoped the continuity of these activities can be maintained.

Assignments for NEANDC-INDC Discrepancy Files

1. σ (n,f) and fission ratios for U-235 (100 eV - 15 MeV), Pu-239 (15 eV - 100 keV), and U-233 (100 keV - 10 MeV)
   Sowerby (UK) and Fort (France)
2. σ (n,γ) for U-238 (1 keV - 1 MeV) and resolved resonance parameters
   Jackson (US)
3. σ (n,n') for U-238 (particularly for 45 keV state) and for the range (1 - 3 MeV)
   Smith (US)
4. $\bar{\sigma}$ (n,f) in fission spectrum for U-238 and the U-238/U-235 ratio (thr. - 20 MeV)
   Knitter (BCMN)

5. Thermal parameters for the fissile nuclei
   Schmidt (IAEA)
6. Delayed neutron yield for U-238 (2 - 3 MeV)
   Smith (US)
7. σ (n, γ) for structural materials - (1 keV - 200 keV)
   Fröhner (Germany)
8. Γ_{γ} for 2.85 keV resonance in Na-23
   Jackson (US)
9. $\bar{\nu}_p$ (E) for U-235 and Pu-239 in the 1 keV to 14 MeV region
   Tsukada (Japan)
10. Parameters for capture in Ni-59
    R. E. Chrien (U.S.)
11. Neutron-induced subthreshold fission in Th-232
    R. E. Chrien (U.S.)
12. σ (n, f) for Am-241
    M. G. Sowerby (UK)

B. Discrepancy Entries

1. σ(n,f) and fission ratios for U-233, U-235, and Pu-239

a. σ_{nf} for U-235

Description of data and its application

Fission cross section of U-235 between 100 eV and 15 MeV. The data are required for the calculations of reactor properties and for use as a standard. Because of the structure in the cross-section observed below 200-300 keV it is desirable to limit its use as a standard to higher energies.

Nature of discrepancies

The data on the U-235 fission cross section have recently been reviewed by the NEANDC/NEACRP Specialists Meeting on the fission cross-sections of U-233, U-235, U-238 and Pu-239. The Conclusions were that, with the exception of the energy range 0.25 to 0.4 MeV, the cross-section is known between 10 keV and 15 MeV with an accuracy of ± 3% (1 σ). The accuracy in the energy range 0.25 to 0.4 MeV is ~ ± 5%. Above 15 MeV the situation is much worse as the data appear to divide into two groups which are up to 15% apart. Below 10 keV the meeting came to no general conclusions on accuracy but values of ~ ± 3 to 5% appear to be reasonable.

These accuracies meet the least stringent requests in WRENDA-75 for data with accuracy of ± ~ 3-5% but are a long way from meeting the many requests for a 1 to 2% accuracy.

Status

The proceedings of the NEANDC/NEACRP Specialist Meeting* includes as a supplement an excellent summary of the available fission cross-section data including graphical comparisons of the various experiments. The experiments on the absolute U-235 measurements considered at the Meeting are given in the table. Some of these measurements are still incomplete and a number of other experiments are either planned or are in progress.

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*Proceedings of the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-sections of U-233, U-235, U-238 and Pu-239. ANL-76-90, NEANDC(US)-199L, ERDA-NDC-5/L To be published.

Comments and recommendations

In order to meet the requirements for higher accuracy (± 2% is a reasonable first objective) further measurements are required. In these measurements it is necessary to resolve the local discrepancy between 0.25 and 0.4 MeV and the more major discrepancy above 15 MeV. Though the latter tends to be outside the energy range of interest it must be resolved as it could be due to effects which could influence the data at lower energies.

In order to achieve these higher accuracies it is necessary to:

(1) make individual measurements more precise by improving and reducing the corrections which must be applied to the raw data,

(2) improve the documentation of experiments as a high accuracy can only be justified if there is detailed documentation

(3) use a variety of techniques and detectors. The importance of spot point data should not be forgotten at a time when many measurements are being made with "white spectrum" neutron sources.

In designingexperimental programmes to obtain accurate values of fission cross-sections the following points should not be forgotten:

(1) it is desirable to make measurements which extend into energy ranges (e.g. thermal 14 MeV) where the highest accuracy data are already available or will be in the future,

(2) the cross sections should be over determined by the data (viz. one should measure U-235(n,f), U-238(n,f), Pu-239(n,f) and all their ratios). This is important because (a) it helps to identify the systematic errors of experiments as these may be different for the various isotopes and (b) the present accuracy of U-235 and the ratios does not give accurate enough values of the fission cross sections of U-238 and Pu-239,

(3) one of the most important corrections to raw experimental data is the subtraction of background. The origins of background are rarely well understood in detail and there can be serious systematic errors in its determination. There is, therefore, a need to investigate this topic so that the errors in background determinations are as small as those due to mass assay and fragment angular distributions for instance.

M. G. Sowerby
November, 1976

U-235 fission cross-section measurements considered by the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-sections of U-233, U-235, U-238 and Pu-239

Set	Name	Reference	Source/Status	Comments
1	Gwin	ANS 15, 481	CSISRS	
2	Grundl	76 ANL	CSISRS	Av. over Cf spectrum
3	Gilliam + R	76 ANL	PC	New values
4	Poenitz	NSE 53, 370	CSISRS	
5	Hansen	76 ANL	CSISRS	
6	Czirr + S	NSE 57, 18	CSISRS	Shape only
7	Czirr	UCRL-77377	CSISRS	Rel. Li-6, new values
8	Kaeppelar	7 Vienna	CSISRS	Also ANL 70
9	Gayther	75 Wash	CSISRS	Shape only
10	Cance	76 ANL	CCDN	
11	Gorlove	AE6, 453	CSISRS	
12	Chelnokov	AE 31, 103	CSISRS	
13	Kuks	73 Kiev	CSISRS	
14	Smith	BAP 2, 196	CSISRS	
15	Henkel-LE	LA-2122	CSISRS	
16	Poenitz 68W	68 Wash	CSISRS	
17	Melkonian	NSE 3, 435	CSISRS	
18	Yeater	PR 104, 479	CSISRS	
19	Diven PR	PR 105, 1350	CSISRS	
20	Williams	LA-150	CSISRS	
21	Nyer	LAMS-938	CSISRS	
22	Whal	LA-1681	CSISRS	
23	Moat	JNE 16, 270	CSISRS	
24	Adams	JNE 14, 85	CSISRS	Shape only
25	White	JNE 19, 325	CSISRS	
26	Perkin	JN 19, 425	CSISRS	Sb-Be source
27	Knoll + P	JNE 21, 643	CSISRS	
28	Netter	CEA-1913	CSISRS	
29	Allen	PPS/A70, 573	CSISRS	
31	Pankratov	AE, JNE 16, 494	CSISRS	Several sets
34	Goldanski	DOK 101, 1027	CSISRS/HOLD	Energies unclear
35	Szabo	76 ANL	CSISRS, CCDN	Several sets, latest values
36	Blons	NSE 51, 130	CSISRS, BHAT	
37	Hall	LA-128	PAPER	
38	Adamov	75 Kiev	PAPER	Av. Cf spectra
39	Benedict		NOT YET	
40	Van Shi-Di	65 Salzburg	BHAT	Requested from NNCSC
42	Dorofeev	JNE 5, 217	PAPER	
43	Lemley	NSE 43, 281	BHAT	
44	Wagemans	ANE, t.b.p.	CCDN	New data
45	Michaudon		BHAT	Some values missing
46	Perez	NSE 55, 203	BHAT	Some values missing
47	Wasson	76 ANL	PC	New data
48	DeSaussure	ORNL-1804	BHAT	
49	Ryabov	INDC-31/U	BHAT	
50	Taschek	LA-445	PAPER	
51	Bowman	66 Wash	BHAT	
52	Schomberg	JNE 24, 269	PAPER	
53	Bailey	LA 447	PAPER	
54	Deruytter		BHAT	
55	Shore	PR 112, 191	BHAT	
56	Cierjacks	76 ANL	PC	Relative H(n,n)
57	Brooks	66 San Diego	NOT YET	
58	Zhuravlev	76 Lowell		

b. σ(n,f) and fission ratios for Pu-239

Description of data and its application

Fission cross section of Pu-239 in the energy range 15 eV to 15 MeV. Above 30 keV many measurements are made relative to the U-235 fission cross section and hence these ratio data must also be considered in this file. Values of the fission cross section are required for the calculation of reactor, particularly fast reactor properties.

Nature of discrepancy

The available data above 10 keV were considered by the NEANDC/NEACRP Specialists Meeting on the Fission Cross Sections of U-233, U-235, U-238 and Pu-239. It is clear from the proceedings* that the Pu-239/U-235 fission cross-section ratio is known to no better than ~ ± 3-4% between 10 keV and 15 MeV and this combined with uncertainties of ~ ± 3% in the U-235 fission cross section suggests that the Pu-239 data can be deduced with an accuracy of between ± 4 and 5%. In addition, however, it is important to consider the direct measurements of the cross sections and there are modern measurements covering the energy range up to 5.5 MeV. Between 10 keV and 1 MeV the estimated accuracy of these data is ~ ± 4% but above 1 MeV this increases to ~ ± 5% as all the data are essentially the work of one group (Szabo and his co-workers). Since the direct and indirect measurements are reasonably consistent the results can be combined and the resulting cross-section accuracy must be ~ ± 3% between 0.01 and 1 MeV increasing to ~ ± 4% between 1 and 5 MeV and ± 5% at higher energies. Between 15 eV and 10 keV the best values necessarily come from direct measurements and the accuracy is typically ~ ± 3 to 4%. These accuracies do not meet the requirements in WRENDA-75 particularly above 10 keV where ± 1% is requested. A number of ± 3-5% requests would, however, appear to be met.

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*Proceedings of the NEANDC/NEACRP Specialists Meeting on the Fast Fission Cross-Sections of U-233, U-235, U-238 and Pu-239. ANL-76-90, NEANDC(US)-199L, ERDA-NDC-5/L To be published.

Status

Reference (*) includes as a supplement an excellent summary of the available data on Pu-239 and experiments considered are listed in the table. It can be seen that some experiments are still in progress.

Comments and recommendations

In order to meet the requirements for higher accuracy more measurements are required and most of the recommendations made in the discrepancy file for U-235 apply to Pu-239. The Specialist Meeting noted that there are systematic errors in the Pu-239/U-235 ratio measurements which appear to indicate errors either in the mass of Pu-239 used or in the efficiency of the detectors. The problem may be due to the higher specific α-activity of plutonium and special attention should be paid to understanding the effects of this on cross-section measurements.

M. G. Sowerby

Pu-239 fission cross-section data considered by the NEANDC/NEACRP Specialist Meeting on the Fast Fission Cross-sections of U-233, U-235, U-238 and Pu-239

Pu-239/U-235 File

Set	Name	Reference	Source/Status	Comments
1	Letho	NSE 39, 361	CSISRS	
2	Poenitz	NSE 47, 228	CSISRS	Two sets
3	Gwin	ANS 15, 481	CSISRS	
4	Carlson	76 ANL	PC	New data, present status, '76
5	Pfletschinger	NSE 40, 375	CSISRS	
6	Gayther	75 Wash	CSISRS	Shape only
7	Savin	YFI-8, 12	CSISRS	Shows structure
8	Smirenkin N	ICD-4	CSISRS	
9	Chelnokov	AE 31, 103	CSISRS	
10	Whal	LA-1681	CSISRS	
11	Williams	LA-520	CSISRS	
12	White	JNE, 65 Salz.	PAPER, CSISRS	Returned to ratio
13	Uttley	AERE-1996	CSISRS	
14	Gilboy	66 Paris	CSISRS	Only lower set valid
15	Soleilac	70 Hels.	CSISRS	
16	Szabo	76 ANL	CSISRS, CCDN	
17	Perkin	JNE 19, 423	DER-CSISRS	From absolute values
18	Netter	JPR 17, 565	DER-CSISRS	
19	Allen	PPS/A70, 573	PAPER	Av. between two poss. values
20	Dorofeev	JNE 5, 217	PAPER	
21	Meadows	76 ANL	PC	New data
22	Iyer	69 ROORKEE	DER-CSISRS	
23	Smith	APS	NOT YET	Pu status unclear
24	Henkel	LA	NOT YET	Unclear reference CS
25	Adams	JNE 14, 85	DER-CSISRS	Shape only
26	Knoll	76 ANL	PC	Formed from abs. values
27	Smirenkin	AE, SAE 13, 974	DER-CSISRS	
28	Moat	AHSB(S)R169	PAPER	
29	Fursov	75 Kiev	IAEA	
30	Cierjacks	76 ANL	NOT YET	
31	Kaeppeler		NOT YET	From absolute values

Pu-239 File

Set	Name	Reference	Source/Status	Comments
1	Gwin	NSE 45, 25	CSISRS	Several sets
3	Weston	ANS 15, 480	CSISRS	
4	Knoll	76 ANL	PC	New data
5	Gayther	75 Wash	CSISRS	
6	Schomberg	70 Hels.	CSISRS	
9	Chalnokov	AE 31, 103	CSISRS	
10	Cote	BAP 1, 187	CSISRS	

Set	Name	Reference	Source/Status	Comments
11	Smith	BAP 2, 196	CSISRS	
13	Moat	JNE 14, 85	CSISRS	
14	Adams	JNE 14, 85	CSISRS	
15	Perkin	JNE 19, 423	CSISRS	Sb-Be source
16	Netter	JPR 17, 565	CSISRS	
17	Allen	PPS/A70, 573	CSISRS	
18	Dorofeev	JNE 5, 217	CSISRS	
20	Smirenkin	AE 13, 366	CSISRS	
21	Dubrovina	DOK 157, 561	CSISRS	
22	Kalinin	58 Geneva	CSISRS	
23	Szabo	76 ANL	CSISRS/CCDN	Presently valid data
24	Blons	70 Hels.	CSISRS	
25	Kaeppeler		NOT YET	Relative H(n,n)

c. $\sigma(n,f)$ and fission ratios for ^{233}U

Requests

The requests are motivated by the studies on the Thorium fuel cycle. According to the WRENDA list, they concern essentially the ratio to the ^{235}U fission cross section (σ_f^3/σ_f^5) with accuracies from 1% to 5% and priorities from 1 to 3. The absolute cross section is also requested with accuracy better than 10%.

Published results

I - Experimental data

a) Fission cross section of ^{233}U.

Several results exist (see Fig. 1) but the discrepancies can exceed 20%, especially in the range 300 keV - 500 keV and 1 MeV - 3 MeV. The causes are probably to be investigated in the experimental techniques used (fission chamber, scintillators, slowing down spectrometer) and in their specific correction rather than in errors in the energy scale.

Nevertheless, a somewhat good convergence must be noted between the "old" values of Harwell[1] and Saclay[2], and the recent values of Oak Ridge[3], and Los Alamos[4]. The last disagree for energies greater than ~ 700 keV and become more and more suspicious when the energy increases.

At higher energies there is also an agreement between values from Los Alamos[5] and from USSR[6]. But these old values should probably be revised, taking into account the improvements realized since the publication in the fields of the nuclear instrumentation and in the knowledge of the parasistic experimental effects.

b) Ratio σ_f^3/σ_f^5

If we neglect the first data from Livermore[7] affected by large fluctuation which cannot be explained by structure in the fission cross sections of ^{233}U and ^{235}U, we find good agreement (see Figs. 2 & 3) between the most recent data of Livermore[8] and those of Karlsruhe[9] obtained by different experimental techniques (fission chamber, flowing gas scintillation). The data of Argonne[10] are systematically higher by 4% than the previous ones. Data from Obninsk[11] are also in agreement within 4% with the Livermore and Karlsruhe data.

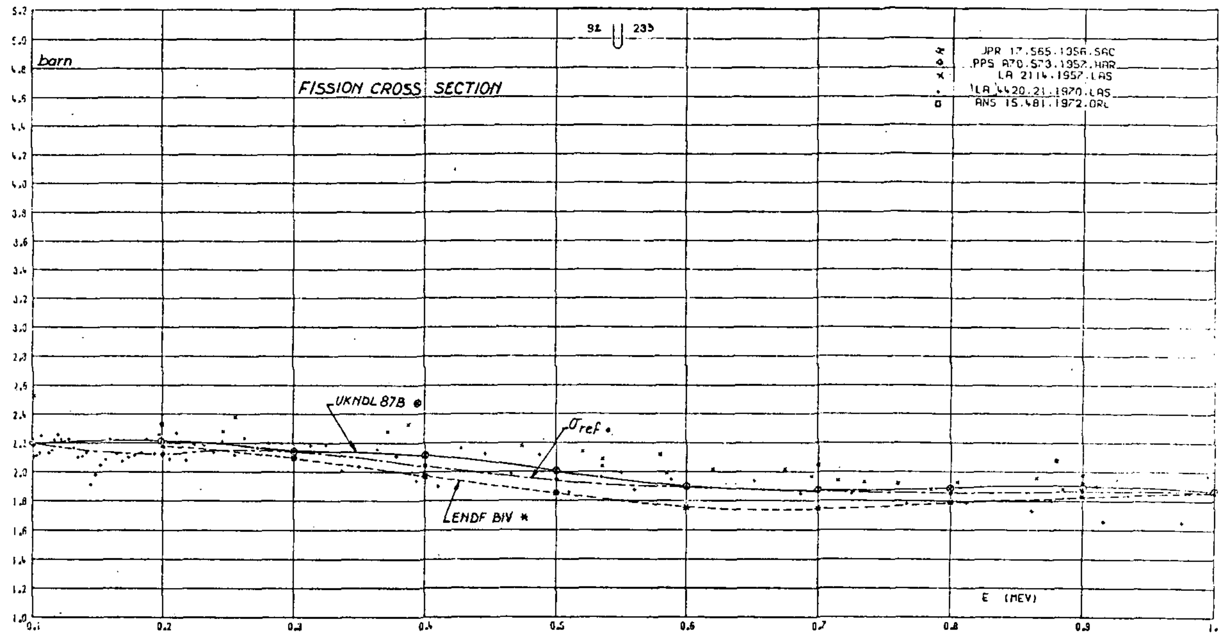


Figure 1

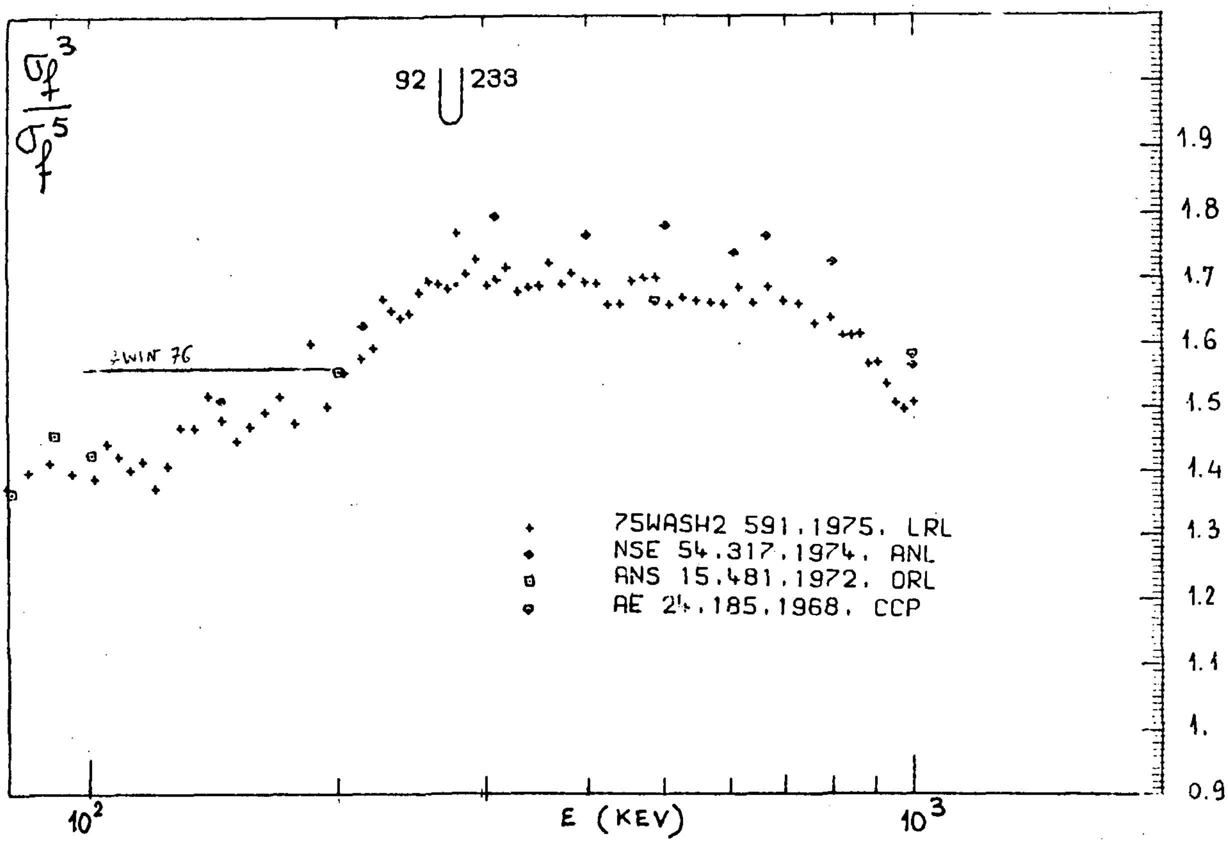
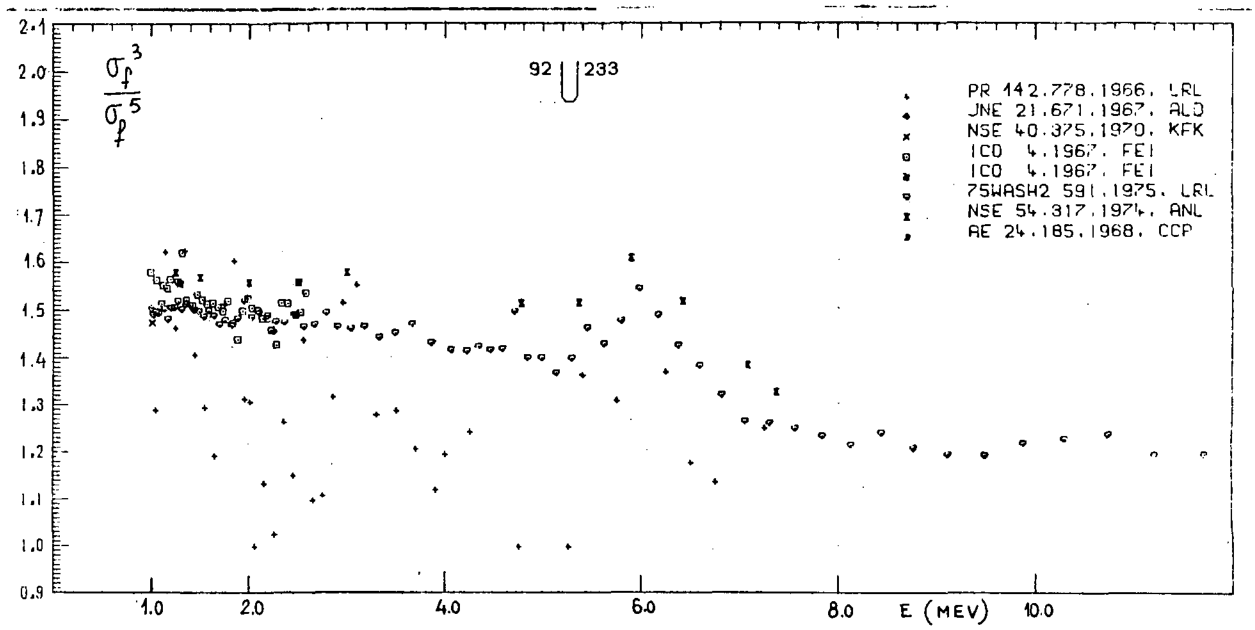


Figure 2



2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
σf3 / σf5
92 U 233
PR 142.778.1966, LRL
JNE 21.671.1967, ALD
NSE 40.375.1970, KFK
ICO 4.1967, FEI
ICO 4.1967, FEI
75WASH2 591.1975, LRL
NSE 54.317.1974, ANL
AE 24.185.1968, CCP
1.0
2.0
4.0
6.0
8.0
E (MEV)
10.0

Figure 3

II - Evaluated data

The evaluations of the fission cross section of ^{233}U are not very numerous. In addition to ENDF/B IV, the most recent evaluations, indexed in CINDA are a British evaluation[14], and a French evaluation[15], the latter being limited to energies greater than 1 MeV. These are shown in Fig. 4.

Between 100 keV and 1 MeV, the agreement in mean values between ENDF/B IV and British evaluation is better than 7%. The latter is close (< 3%) to a curve σ_{ref} deduced from the ratio $\sigma_f 3/\sigma_f 5$ [8,9] and from Sowerby's evaluation[11] of $\sigma_f 5$.

For the energy range (1 MeV - 2.6 MeV) the three evaluations mentioned above and the curve σ_{ref} agree within less than 5%. For other energies the agreement lies within 10%.

It must be noted that the curve σ_f^3/σ_f^5 extracted from ENDF/B IV is not supported by any recent measurement between 100 keV and 800 keV.

Conclusions

It seems that the experimental effort of the last years has improved the knowledge of the ratio σ_f^3/σ_f^5 which can be considered as known with an accuracy of 4% on the whole energy range. Since the evaluation for σ_{nf}U233 are coherent with what can be obtained from σ_f^3/σ_f^5, from the knowledge (± 3%) of σ_{nf}(U-235) one can conclude that this cross section is determined between 100 keV and 2.6 MeV with an accuracy of 5%.

It has to be noted that a precision of 1% on σ_f^3/σ_f^5 gives at the present time, a precision of only ≈ 4% on σ_{nf}(U-233). Therefore future improvements in the precision of σ_{nf}(U-233) are more likely if the experimental effort is put on the absolute determination of σ_{nf}(U-233), specially for energies greater than 2.6 MeV.

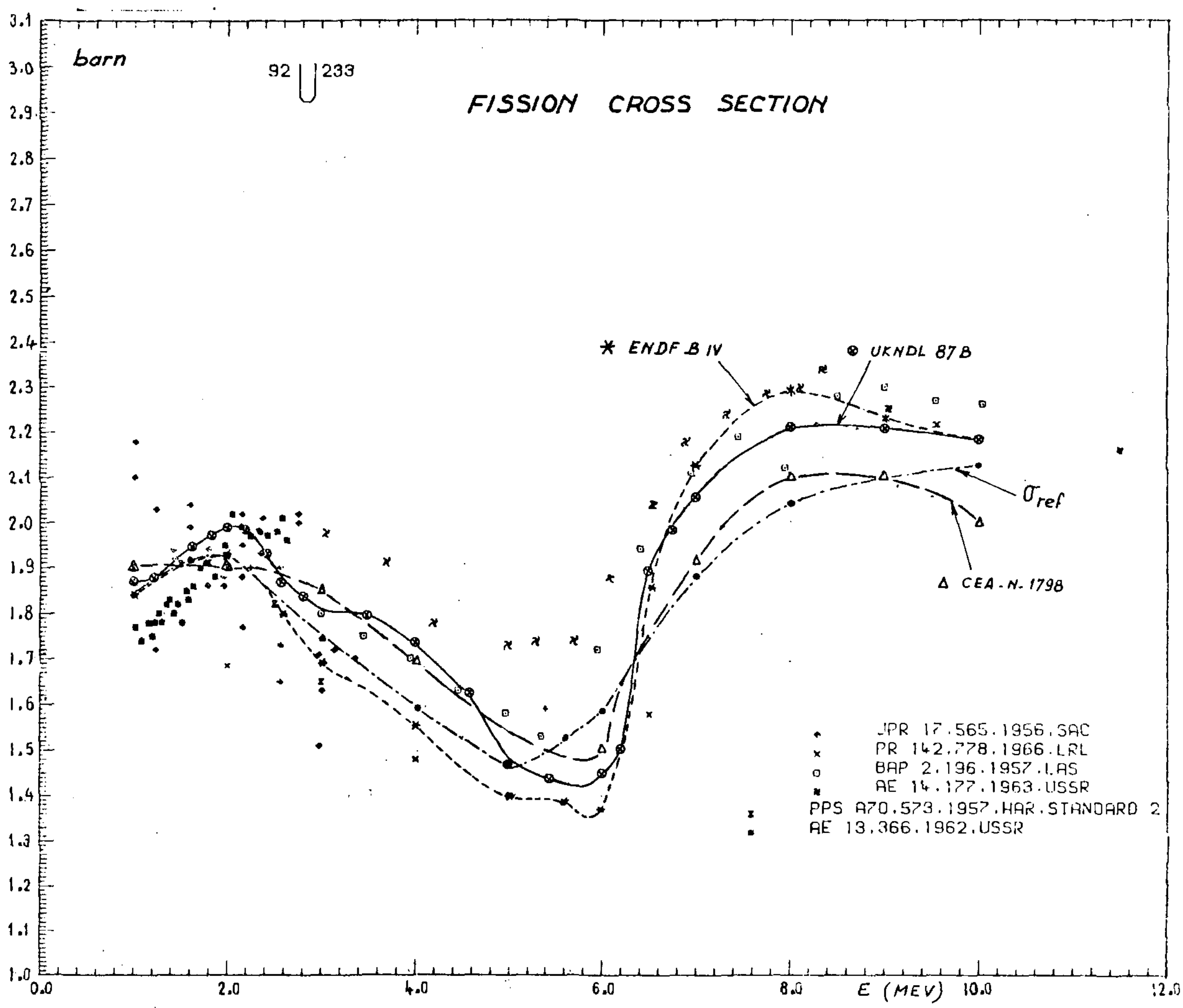
Experimental data for the secondary fission channels (n, γ f), (n, n'f), (n, 2nf) should be useful for the evaluation.

ESTIMATIONS OF THE ACCURACIES

Energy range	σ_f^3/σ_f^5	σ_f^3
100 keV-2.6 MeV	4%	5%
2.6 MeV-10 MeV	4%	10%

E. Fort
November, 1976

1 PPS A70, 573, 1957, HAR
2 JPR, 17, 565, 1956, SAC
3 ANS 15, 481, 1972, ORL
4 LA, 4420,21, 1970, LAS
5 BAP 2, 196, 1957, SAC
6 Geneva Conf 2, 16, 136, 1958, USSR
7 PR, 142, 778, 1966, LRL
8 75 WASH 2, 591, 1975, LRL
9 NSE, 40, 375, 1970, KFK
10 NSE 54, 317, 1974, ANL
11 ICD 4, 1967, FEI
12 M. G. SOWERBY, NEANDC (UK) 160, 1974
13 NSE, 59, 79, 1976
14 UKNDL DFN 87B, 1973
15 CEA-N-1798, 107, 1975


barn
92 U 233
FISSION CROSS SECTION
ENDF.B IV
UKNDL 87B
σref
CEA-N-1798
JPR 17.565.1956.SAC
PR 142.778.1966.LRL
BAP 2.196.1957.LAS
AE 14.177.1963.USSR
PPS A70.573.1957.HAR.STANDARD 2
AE 13.366.1962.USSR
E (MEV)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1

2. $\sigma(n,\gamma)$ for ^{238}U (1 keV - 1 MeV) and resolved resonance parameters

Description and application

A precise knowledge of the resonance parameters and the corresponding cross sections is essential to the prediction of reactivity and related properties of LWR lattices and fast reactor critical assemblies. An accurate knowledge of the capture cross section for ^{238}U in the 1 keV to 1 MeV region is fundamental to prediction of neutron absorption and breeding ratio in a fast breeder system. Unfortunately despite the continuing advances in the technology of cross section measurements for ^{238}U, measurements of resonance parameters and of capture cross sections in the unresolved higher energy regions from different laboratories show presistent and unexplained discrepancies well outside limits one may reasonably expect.

Nature of the discrepancy

Measurements in the region above 4 keV published since 1969 include:

Authors	Lab	Year	Accuracy
Moxon	Harwell	1969	4—8%
Friesenhahn et al.	GA	1970	6—10%
de Saussure et al.	ORNL	1973	5—10%
Spencer & Kappler	KFK	1975	~ 11%

ORNL and AERE for σ_γ of ^{238}U data differ in normalization up to 10% below 30 keV. In general discrepancies among the data sets are as large as 20% although uncertainties quotes by various groups are much smaller. GRT data above 100 keV seem lower than older data. Recent UK data support lower values. Two sets of ORNL data agree within errors when normalized to the same $^{235}U(n,f)$ data. With regard to studies of resolved resonances in the 1-4 keV region widths of individual resonances as measured at Geel and Columbia differ by more than combined error. A recent analysis of Moxon shows strong correlations of the discrepancies with neutron energy and suggests that systematic errors have not been properly evaluated and error assignments are probably over optimistic.

Status

In a recent report on ^{238}U Neutron width evaluations (see BNL-NCS-50451, page 156) H. Derrien has summarized the present situation and pointed out that it is very likely that the problem lay in the procedures followed in analyzing the experimental data. Using a least-squares shape analysis he has reanalyzed a limited portion of the data of Rahn et al. (Columbia) and Carraro et al. (Geel) and in contrast to their published results he finds a consistent set of parameters for the resonances analyzed. In addition a new series of measurements is in progress at Geel and preliminary results were reported at the 1975 Washington Cross Section and Technology Conference. Definitive ORNL data will appear shortly, (Olsen et al. -NSE to be published.)

Comments and recommendations

The analysis of Derrien indicates that the central problem is the analysis technique. At present it appears that major effort should be concentrated on obtaining a detailed body of data for each measurement with adequate supporting information to permit a precise independent simultaneous analysis of each data set to obtain the relevant resonance parameters. At the same time the procedures followed in obtaining the published results should be carefully reviewed to be certain of their applicability and limitations. Only after these steps have been completed should additional measurements be undertaken.

References

REFERENCES

[1] H. Derrien, BNL-NCS-50451, Seminar on ^{238}U Resonance Capture, p. 156 (1975).

[2] M. C. Moxon, Specialist Meeting on "Resonance Parameters of Fertile Nuclei and ^{239}Pu", Saclay May 1974, NEANDC (E)-163U, p. 159.

[3] F. Poortmans et al., ref. 2, p. 159.

[4] F. Corvi, et al., Proceedings of Conference on Nuclear Cross Sections and Technology, NBS Special Publication 425, 1975, page 733.

[5] F. Rahn and W. W. Havens, Jr., "A review of the Total Radiation Widths of the Neutron Resonances of ^{238}U". EANDC(US) - 179/U. INDC(US)-53/U.

[6] R. R. Spencer and F. Kappeler, reference 4, p. 620.

[7] G. Carraro and W. Kolar, Proceeding Third Conference on Neutron Cross Sections and Technology, Knoxville, 1971, Vol. 2, p. 701.

[8] S. J. Friesenhahn, et al., GA 10194, General Atomics (1970).

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H. E. Jackson
September, 1976

3. The inelastic neutron scattering cross section of ^{238}U

Description and application

The ^{238}U inelastic neutron scattering cross section makes a major contribution to the energy transfer matrix governing neutron distributions within fast reactor systems. The ideal goal is few-percent accuracies in the cross sections for the excitation of discrete or groups of states in ^{238}U to incident neutron energies of approximately 3.0 MeV particularly where large energy transfers are involved. Below incident energies of approximately 1.5 MeV the scattered neutron resolution should be sufficient to resolve the individual components. At incident neutron energies above 1.5 MeV broader scattered-neutron resolutions of several hundred keV probably will suffice providing the desired group-averaged cross-section accuracy is achieved.

Nature of the discrepancy

The discrepancy is primarily in two energy regions:

1. Threshold to $\approx$ 600 keV

At incident energies of $\leqslant$ 600 keV the cross section is dominated by the excitation of the first (2+, 45 keV) excited state. Measured cross-section magnitudes in this region are discrepant by as much as 50%, and shapes are inconsistent between measurements and between measurements and some evaluations and theoretical estimates. This is a high-importance region in the context of a typical fast reactor spectrum.

2. 1–3 MeV

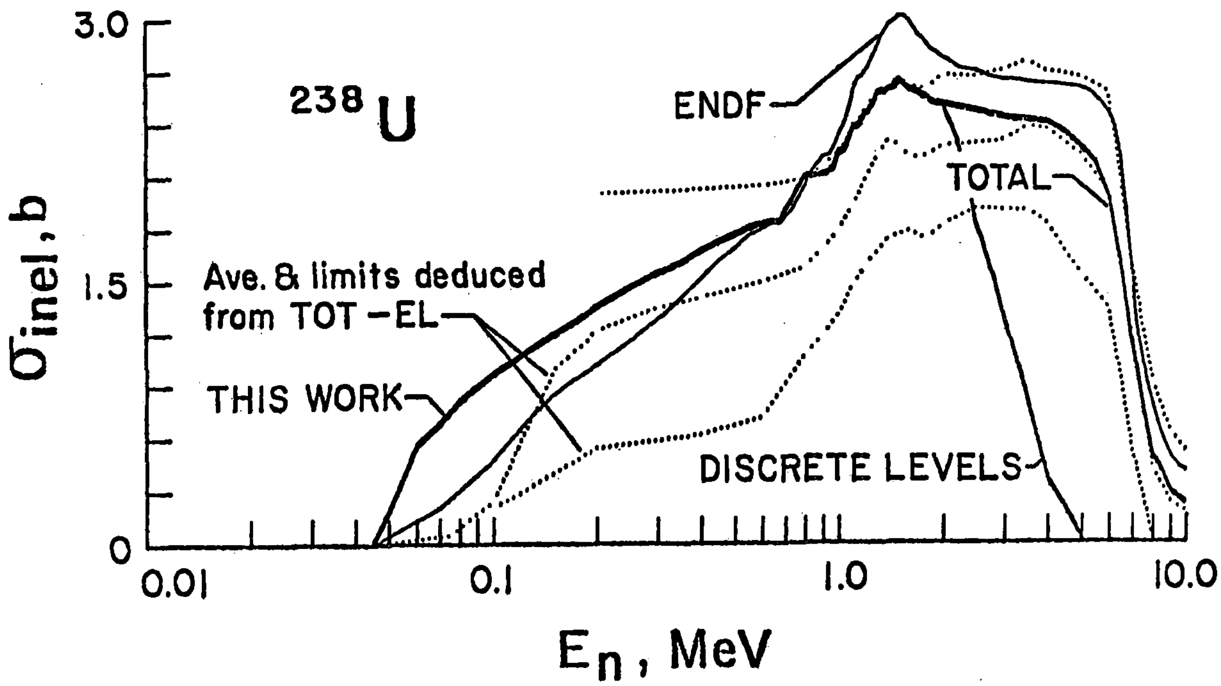
The contributing excited structure in this region is complex and uncertain and measured microscopic cross sections are sparse and have large errors. The microscopic measured values and those often implied by determinations of the non-elastic cross section tend to be 20–30% larger than deduced from a number of macroscopic studies.[1] This discrepancy can amount to as much as 1/2 a barn which is difficult to reconcile with uncertainty estimates associated with the microscopic experimental determinations or theoretical estimates.

Low energy ($\leq$ 600 keV) status

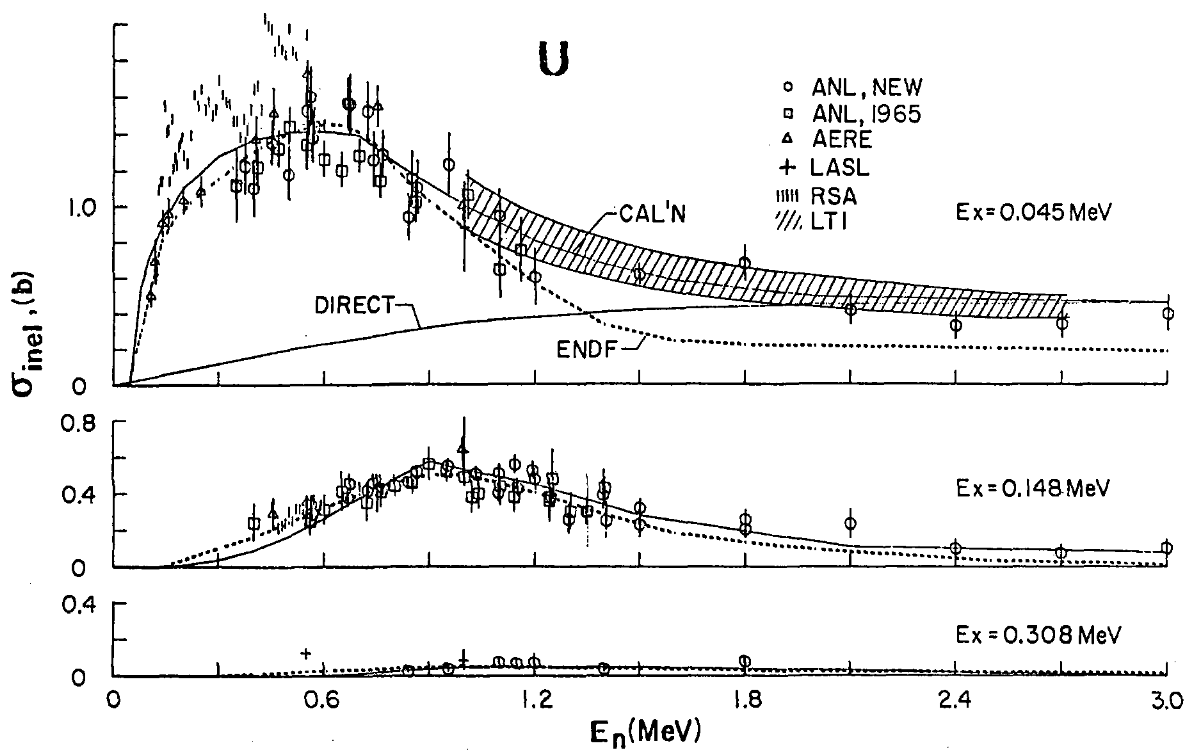
The contemporary knowledge of this low-energy region is outlined in Fig. 1. Recent measurements have greatly improved the understanding of the excitation of the ground-state rotational band at energies above 600 keV with impact upon the interpretation of the inelastic cross section at higher energies.[2,3] However, at lower energies the cross section remains largely an enigma. The primary data sets are from AERE,[4] two from ANL,[2] from South Africa[5] and a single energy value from LASL.[6] The AERE and ANL results are qualitatively consistent but there is a trend for the latter to be systematically lower by about 10%. The single LASL point at approximately 550 keV lies between the AERE and ANL values. Part of the uncertainties in the angle-integrated values may be due to a lack of knowledge of the angular distributions. However, the latter have been measured at both LASL and ANL with reasonable agreement and thus there is some confidence in the interpretation of single-angle values (e.g., 90 deg. values of Ref. 4). The South African results are much larger than those of ANL, AERE or LASL and display a unique structure.

The above data base is not quantitatively consistent in the energy region 500-600 keV. The discrepancies are a minimum of 10%. This is a critical area as it governs the normalization of measured and calculated cross-section shapes to threshold. It is also an energy region that is most favorable from an experimental point of view. As the energy decreases below 500 keV the discrepancies increase to as much as 50%. In addition the energy dependent shapes are discrepant. Moreover, some of the experimental shapes do not follow the predictions of the simple Hauser-Feshbach formalism. Faced with these ambiguities, the evaluations are guided by macroscopic comparisons as illustrated by the ENDF-IV result shown in Fig. 1. This particular evaluation is not consistent with the shape predicted by the Hauser-Feshbach formula as applied at several institutions.[7,8] Thus there are theoretical, in addition to experimental questions involved.

The above problem area is being attacked by at least three laboratories. A conventional low-noise neutron detector is being employed at ANL down to energies of approximately 200 keV and a new device shows



238 U
ENDF
TOTAL
Ave. & limits deduced from TOT −EL
THIS WORK
DISCRETE LEVELS
σinel, b
En, MeV



U
ANL, NEW
ANL, 1965
AERE
LASL
RSA
LTI
CAL'N
DIRECT
ENDF
Ex=0.045 MeV
Ex=0.148 MeV
Ex=0.308 MeV
σinel, (b)
En(MeV)

promise for measurements to essentially threshold. An attempt will be made at ORNL to measure the gamma-rays emitted following the inelastic scattering process in the few hundred keV incident neutron energy range. Measurements at energies of 400-600 keV are apparently underway in Sweden. In addition, a careful measurement of the scattered neutron angular distribution at 550 keV is underway at ANL with the objective of determining the cross section at this optimum energy to 5% accuracy.

High energy (1—3 MeV) status

For a number of years macroscopic studies have continued to imply that the ^{238}U inelastic scattering cross section in this energy range is 20—30% lower than indicated by microscopic measurements. This is illustrated by recent pulsed-assembly results at RPI and SNEAK studies at KFK.[1] The microscopic results are sparse and largely confined to results obtained at AERE[4] and ANL.[7,9] Recent measurements at Lowell[3] and ANL[2] have given improved definition to the inelastic neutron excitation of the ground-state rotational band. These new results influence the interpretation of the higher excitations but do not directly address the primary high-energy problem (i.e., the energy transfers associated with the excitation of the ground-state band are a relatively small 45 and 145 keV). The structure contributing to cross sections in this energy range is not well known[10,11] but certainly very complex. In addition, measurements are complicated by the increasing prevalence of fission neutrons with increasing incident neutron energy. Alternative approaches have been based upon the better experimentally-defined non-elastic cross section (i.e., difference between well known total and reasonably known elastic scattering cross sections). Using this latter approach one recent evaluation has achieved reasonable consistency between measured total inelastic cross sections and non-elastic cross sections (see Fig. 2)[7] but other interpretations have lead to pronouncedly smaller inelastic cross sections.[1]

Measurements with the objective of resolving the above uncertainty are in progress, primarily at AERE and ANL.[12] Both groups employ fast time-of-flight techniques. The ANL study attempts to resolve discrete excitation functions to 2.0 MeV and above. The AERE approach tends more toward group inelastic cross sections with broader resolution ($\approx$ 200 keV). Preliminary results have been obtained in both programs. The ANL results give improved understanding to $\approx$ 1.5 MeV and are generally consistent with previous microscopic measurements. The AERE preliminary values tend to indicate larger (not smaller) inelastic cross sections in the incident neutron energy range 1—3 MeV. This new information may warrant a re-evaluation of the situation, up to 1.5—2.0 MeV, particularly including the new understanding of elastic scattering (therefore non-elastic cross sections). The available information at higher energies remains far more ambiguous.

Recommendations and suggestions

1) The inelastic cross section should be determined to $\approx$ 5% accuracy at a standard reference energy of $\approx$ 550 keV with a resolution of $\approx$ 10 keV. The measurement should include a determination of the differential distribution with sufficient precision to provide the angle-integrated cross section to the above accuracy goal.

2) Relative measurements should be made at $\approx$ 100 keV incident energy intervals from threshold to the above 550 keV reference value. They need not necessarily be absolute.

3) When measurements are made at a single scattering angle it is suggested that 90 deg. be used so that values obtained at various laboratories can be easily compared. In addition, it is suggested that a measurement of scattering from a secondary standard be made concurrently with the ^{238}U studies and carbon is suggested for that purpose.

4) Some measurements should be made near 400 keV with sufficient incident neutron resolution and detail to confirm or refute structure observed in some of the reported results.

5) Measurements above the fission threshold would be a valued contribution if reported as neutron emission cross sections and/or with rather broad (200—300 keV) scattered neutron resolutions.

6) Multiple events may significantly perturb the measured values therefore attention should be given to correction procedures and it is suggested that results be reported as obtained both prior to and after correction.

7) Contemporary advances in the understanding of the compound nucleus and direct reaction processes have a potential for improved interpretation and extrapolation of measured values. These theoretical concepts should be put in a readily usable form and applied to this problem area.

8) A continuing limitation to definitive interpretation is a lack of knowledge of the structure of ^{238}U at excitation energies above ≈ 1.0 MeV. Basic structure studies alleviating this shortfall would greatly assist in the quantitative interpretation of the very difficult direct measurements of this inelastic neutron scattering process.

Note: This problem is under active review by the CSWEG, NNCSC, Brookhaven National Lab. and a new data file in ENDF-V is expected in the near future.

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[11]SUNI Annual Report (1973).

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4. $\bar{\sigma}(n,f)$ for ^{238}U and $^{238}U/^{235}U$ Fission ratio (thr-20 MeV) in fission neutron spectrum

a. $\sigma(n,f)$ for ^{238}U

Description of datum and its application

The average cross section of ^{238}U for fission neutrons induced by thermal neutrons on ^{235}U is defined by the equation

$$\bar{\sigma}_F\,(N_{25},\,^{238}U) = \int_0^\infty \sigma_{F28}(E)\, N_{25}\,(E)\, dE$$

with $\int_0^\infty N_{25}\,(E)\, dE = 1$

where $N_{25}(E)$ is the normalized fission neutron spectrum of ^{235}U induced by thermal neutrons

$\sigma_{F28}(E)$ is the neutron induced fission cross section of ^{238}U as a function of the neutron energy

Field of application: neutron dosimetry

Status

This quantity can be obtained in three different ways: by direct measurement[1], by calculation from differential data[2,3,4,5] and from reaction rate ratio measurements taking one average cross section as a reference. A recent, comprehensive evaluation of the integral reaction rate data and average cross sections for the ^{235}U fission neutron spectrum is found in ref. 6.

The direct measurement yields a value of

$$\bar{\sigma}\,(N_{25},\,^{238}U) = 313 \pm 3.4 \text{ mb}$$

accepting $\bar{\nu}_{th} = 2.416 \pm 0.005$.

The calculations from differential data sets yield values between

$$286 \text{ mb} \leq \bar{\sigma}\,(N_{25},\,^{238}U) \leq 307 \text{ mb}$$

if a Watt distribution with the parameter A = 1, B = 2 and E = 2.00 MeV is taken.

The reaction rate measurements were evaluated in 1972[7] and 1976[6]. The recommended value from this type of measurements changed from 328 ± 21 mb to now 305 ± 10 mb due to a recent remeasurement of the reference cross section $\bar{\sigma}(N_{25}, {}^{235}U)$[8].

Nature of discrepancy

In the calculations of $\bar{\sigma}(N_{25}, {}^{238}U)$ from differential data sets no error propagation calculations were done. Recent information on the fission neutron spectrum of ^{235}U[9] indicate values of $\bar{E}$ higher than 2.00 MeV. The reaction rate measurements seem to suffer mainly because of the reference cross section.

Comments and recommendation

1. Evaluation of ^{235}U fission neutron spectrum giving due attention to corrections to be applied and to the error components emanating from the neutron energy determination.
2. Calculation of $\bar{\sigma}(N_{25}, {}^{238}U)$ from evaluated data sets including proper calculation of the error.
3. Direct measurement of $\bar{\sigma}(N_{25}, {}^{238}U)$.

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9 November 1976

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[9] H. -H. Knitter and C. Budtz-Jørgensen, private communication.

b. $^{238}U/^{235}U$ ratio

Description of datum and its application

The ratio of the fission cross section of ^{238}U to that of ^{235}U is wanted. The measurement of the ratio of fission cross sections avoids the difficulty of the absolute neutron fluence measurement. Application: reactor calculations.

Status

The NEANDC/NEACRP Specialists' Meeting on Fast Neutron Fission Cross Sections, held at Argonne the 28th to 30th June 1976 has reviewed also this cross section ratio and therefore all relevant references to data may be obtained from the proceedings[1,2]. One believes that an evaluated curve could be obtained with an accuracy of ± 2% below 10 MeV incident neutron energy. Above that, the data are sparse and appear discrepant (≈ 10%).

Nature of discrepancy

The discrepancy above 10 MeV lies perhaps in the detection method(s) used in the measurements (Ionization chamber/gas scintillation detector).

Also below 10 MeV there are some discrepancies between "white source" and "monoenergetic source" measurements concerning the energy scale which have not been cleared up.

Comments and recommendation

The Specialists' Meeting has given a somewhat too optimistic picture of 2% for the fission cross section ratio of $^{238}U/^{235}U$ to be obtained in an evaluation below 10 MeV incident neutron energy if one considers all possible error sources (mass ratio determination detection efficiency and angular distributions of fission fragments, neutron energy scale determination, background determinations etc.).

The recommendations of the above mentioned meeting are:

1. Measurers in the MeV range should include a check on the energy of the 2.07 MeV carbon resonance to confirm the accuracy of MeV energy scales.

2. If differences for the $^{238}U/^{235}U$ ratio in the energy range above 10 MeV are not cleared up by a restudy of existing data, a detector exchange should be initiated to resolve any possible problem between gas scintillators and ionization chambers.

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[2] Suppl. to ANL-76-90, edited by W. P. Poenitz and A. B. Smith.

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5. Thermal Parameters for Fissile Nuclei

Data

^{235}U, ^{233}U, ^{239}Pu, ^{241}Pu 2200 m/s and 20°C Maxwellian average neutron cross sections and fission-neutron yields.

Significance

Thermal fission reactors.
Standard (^{235}U).
Normalization values for cross-section curves at thermal and higher energies.

Status

REFERENCES

H. D. Lemmel, the third IAEA evaluation of the 2200 m/s and 20°C Maxwellian neutron data for ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, Conference on Nuclear Cross Sections and Technology, Washington, D. C., 3—7 March 1975, paper EA2. B. R. Leonard, Jr., Thermal parameters of the fissile isotopes, same Conference, paper EA1.

Discrepancies

For ^{235}U and ^{233}U a systematic discrepancy of about 1.5% is encountered between cross-section measurements with monoenergetic neutrons of 0.0253 eV (2200 m/s), and those made in a thermal neutron spectrum. See table 1. It seems that the fission cross sections of U isotopes measured in a thermal neutron spectrum are systematically too low. No such discrepancies exist for ^{239}Pu and ^{241}Pu.

Sources of uncertainty

a. σ_f^o (^{233}U): no direct determination existing except for an old inaccurate one. Consequently, significant discrepancies for this value exist among recent evaluations. A measurement at Geel is in progress.

b. σ_f^o (^{239}Pu): The accuracy of this quantity suffers from the uncertainty in the ^{239}Pu half life. Several new half-life measurements are in progress showing a tendency to lower half-life values by which the fission cross section would be increased.

c. $\sigma_f^o(^{235}U$ and $\sigma_f^o(^{233}U)$: These cross sections depend much on the knowledge of the half-life values for ^{234}U and ^{233}U, respectively. These half-lives seem to be well established now. However, the confidence in these half-life values and hence in the fission cross-section values is somewhat limited by the fact that the large discrepancies encountered in earlier half-life measurements have not yet been explained.

d. Westcott g factors: The accuracy of the Westcott g factors, g = σ (thermal Maxwellian)/(2200 m/s), is limited by insufficient knowledge of the lowest-energy cross-section curves of the U isotopes (E = 0.005 to 0.025 eV). This uncertainty becomes significant when one corrects integral measurements of α or σ_γ from the experimental neutron temperature to the reference temperature of 20° C.

e. fission-neutron yield data: The accuracy of $\bar{\nu}$ data was previously much limited by the poor accuracy of the standard value of $\bar{\nu}$ (^{252}Cf). This standard seems now to be rather well established. The so-called "$\bar{\nu}$-η-discrepancy" (that is, the apparent discrepancy between the now-reduced $\bar{\nu}$ values and the established relatively high η values), does not exist if both are related to each other through the 2200 m/s cross sections: $\bar{\nu}_t/\eta^o = \sigma_a{}^o/\sigma_f{}^o$. The discrepancy expressed by $\bar{\nu}_t/\eta^o = (1 + \alpha)g_f/g_a$, where the measured α values are too large, is only part of the more general discrepancy between mono-energetic and Maxwellian cross-section measurements discussed above. The accuracy of absolute and relative D data depends on the exact shape of the fission neutron spectra of the fissile nuclides, except when the neutron detector has a flat energy response.

Comments and recommendations

a.) Reexaminations, possibly with new measurements, are needed to find out why the fission cross-section measurements of U isotopes in thermal spectra yield systematically too-low values and why the α measurements in a thermal spectrum yield systematically too-large values, compared with the monoenergetic cross-section measurements, and compared with the fission neutron yield data $\bar{\nu}$ and η. These studies involve:

- Reexamination of irradiation α experiments.
- Reexamination of thermal σ experiments.
- Reevaluation of the accuracy assignment of absolute σ_f^o values.
- Confirmatory high-accuracy measurements of α, σ_f, and σ_f^o.

b.) For the U isotopes, lowest energy cross-section curve shapes, in particular for capture, require confirmatory experiments and simultaneous evaluation of partial and total cross sections. Possible influence of negative-energy resonance needs to be investigated. The accuracy of g factors, g(20°C) and g(T)/g(20°C), requires further studies.

c.) $\sigma_f^o(^{233}U)$ being measured at Geel.

d.) $T_{1/2}(^{239}Pu)$ being measured at various places.

e.) Studies are needed to find out the reason for the previously-measured high half-life values.

f.) Further desirable experiments which would improve the knowledge of the fission neutron yield data for the fissile isotopes include:

- Further investigations of the complex experimental corrections needed in $\bar{\nu}$ and η experiments.
- More precise determinations of the fission neutron spectra and corresponding corrections in $\bar{\nu}$ experimental data.
- Improved thermal fission critical experiments and analysis, particularly for ^{239}Pu.

- Confirmatory measurements relative to the mono-energetic η measurements.

g.) Further desirable experiments which would improve the knowledge of the thermal cross sections of fissile isotopes include:

- Accurate coherent scattering-amplitude measurements in the thermal region.
- Measurement of the total cross section $\sigma_T(E)$ of ^{233}U in the thermal region.

J. Schmidt (IAEA)

Table 1: Discrepancies

	Fit of 2200 m/s data and $\bar{\nu}$ data together	δ	Fit of thermal Maxwellian data alone
σ_f^o	$\sigma_f^o = \sigma_a^o \eta^o / \bar{\nu}_t$		σ_f / g_f
^{233}U	532.6 ± 3.0	4.0	528.6 ± 3.6
^{235}U	587.7 ± 1.9	9.0	578.7 ± 4.0
$^{233}U/^{235}U$	0.906 ± 0.005	0.007	0.913 ± 0.003
$^{239}Pu/^{235}U$	1.269 ± 0.007	0.019	1.288 ± 0.006
$1 + \hat{\alpha}$	$\frac{g_a \sigma_a^o}{g_f \sigma_f} = \frac{\bar{\nu}_t g_a}{\eta^o g_f}$		$1 + \hat{\alpha}$
^{233}U	1.080 ± 0.006	0.010	1.090 ± 0.001
^{235}U	1.157 ± 0.006	0.015	1.172 ± 0.001
$\bar{\nu}_t$	$\bar{\nu}_t = \eta^o \sigma_a^o / \sigma_f^o$		$\hat{\eta}(1 + \hat{\alpha})$
^{233}U	2.469 ± 0.008	0.034	2.503 ± 0.021
^{235}U	2.403 ± 0.006	0.048	2.451 ± 0.019

Table 2: Comparison with other evaluations

		Present work* (1975)	IAEA 1969 [2]	Change	De Volpi [5] (1971)	Steen [G7] (1972)	ENDF/B-4	Fit of 2200 m/s data and $\bar{\nu}$ data (present work)
^{233}U	σ_a	575.2 ± 1.3	577.6 ± 1.8	-2.4	575.6	572.2 ± 0.9	579.9 ± 1.5	573.8 ± 1.8
	σ_f	529.9 ± 1.4	530.6 ± 1.9	-0.7	531.9	526.3 ± 0.8	533.7 ± 1.3	532.6 ± 3.0
	η	2.283 ± 0.006	2.284 ± 0.006	-0.001	2.284	2.277 ± 0.005	2.284 ± 0.004	2.291 ± 0.009
	$\bar{\nu}_t$	2.479 ± 0.006	2.487 ± 0.007	-0.008	2.472	2.476 ± 0.005	2.482 ± 0.005	2.468 ± 0.008
	g_a	1.001 ± 0.002	0.997 ± 0.001	+0.004			0.999	
	g_f	0.997 ± 0.002	0.995 ± 0.002	+0.002			0.997	
	$T_{1/2}$	159000 ± 200	159300 ± 2400	-300				
^{235}U	σ_a	680.9 ± 1.7	678.5 ± 1.7	+2.4	683.0 ± 1.9	675.8 ± 1.3	682.9 ± 1.4	680.6 ± 1.8
	σ_f	583.5 ± 1.3	580.2 ± 1.8	+3.3	585.7 ± 1.8	577.5 ± 1.1	585.7 ± 1.1	587.7 ± 1.9
	η	2.071 ± 0.006	2.072 ± 0.006	-0.001	2.058 ± 0.006	2.062 ± 0.005	2.074 ± 0.003	2.075 ± 0.008
	$\bar{\nu}_t$	2.416 ± 0.005	2.423 ± 0.007	-0.007	2.400 ± 0.007	2.412 ± 0.005	2.419 ± 0.004	2.403 ± 0.006
	g_a	0.980 ± 0.003	0.979 ± 0.001	+0.001			0.979	
	g_f	0.976 ± 0.002	0.977 ± 0.002	-0.001			0.977	
^{234}U	$T_{1/2}$	244700 ± 200	248800 ± 1600	-4100				
^{239}Pu	σ_a	1011.2 ± 4.1	1012.9 ± 4.1	-1.3	1013.4 ± 4.6		1018.8 ± 3.6	1010.8 ± 4.7
	σ_f	744.0 ± 2.5	741.6 ± 3.1	+2.4	742.5 ± 3.1		742.0 ± 2.1	745.9 ± 3.8
	η	2.106 ± 0.007	2.109 ± 0.007	-0.003	2.091 ± 0.007		2.107 ± 0.007	2.112 ± 0.008
	$\bar{\nu}_t$	2.862 ± 0.008	2.880 ± 0.009	-0.018	2.854 ± 0.007		2.873 ± 0.008	2.862 ± 0.010
	g_a	1.081 ± 0.004	1.075 ± 0.003	+0.006			1.075	
	g_f	1.056 ± 0.003	1.055 ± 0.003	+0.001			1.055	
	$T_{1/2}$	24290 ± 70	24380 ± 50	+90				
^{241}Pu	σ_a	1378 ± 9	1375 ± 9	+3			1373 ± 7	1377 ± 13
	σ_f	1015 ± 7	1007 ± 7	+8			1009 ± 4	1021 ± 11
	η	2.155 ± 0.010	2.149 ± 0.014	+0.006			2.156 ± 0.007	2.162 ± 0.013
	$\bar{\nu}_t$	2.294 ± 0.010	2.934 ± 0.012	-0.010			2.934 ± 0.008	2.915 ± 0.010
	g_a	1.039 ± 0.003	1.038 ± 0.001	+0.001		Axton	1.038	
	g_f	1.044 ± 0.005	1.049 ± 0.005	-0.005		[N4] (1972)	1.049	
^{252}Cf	$\bar{\nu}_t$	3.746 ± 0.009	3.765 ± 0.012	-0.019		3.734 ± 0.008	3.757 ± 0.007	3.740 ± 0.009

*H. D. Lemmel in NBS Spec. Pub. 425, Vol 1 page 286 (1975)

6. Total delayed fission neutron yield of ^{238}U

Quantity and application

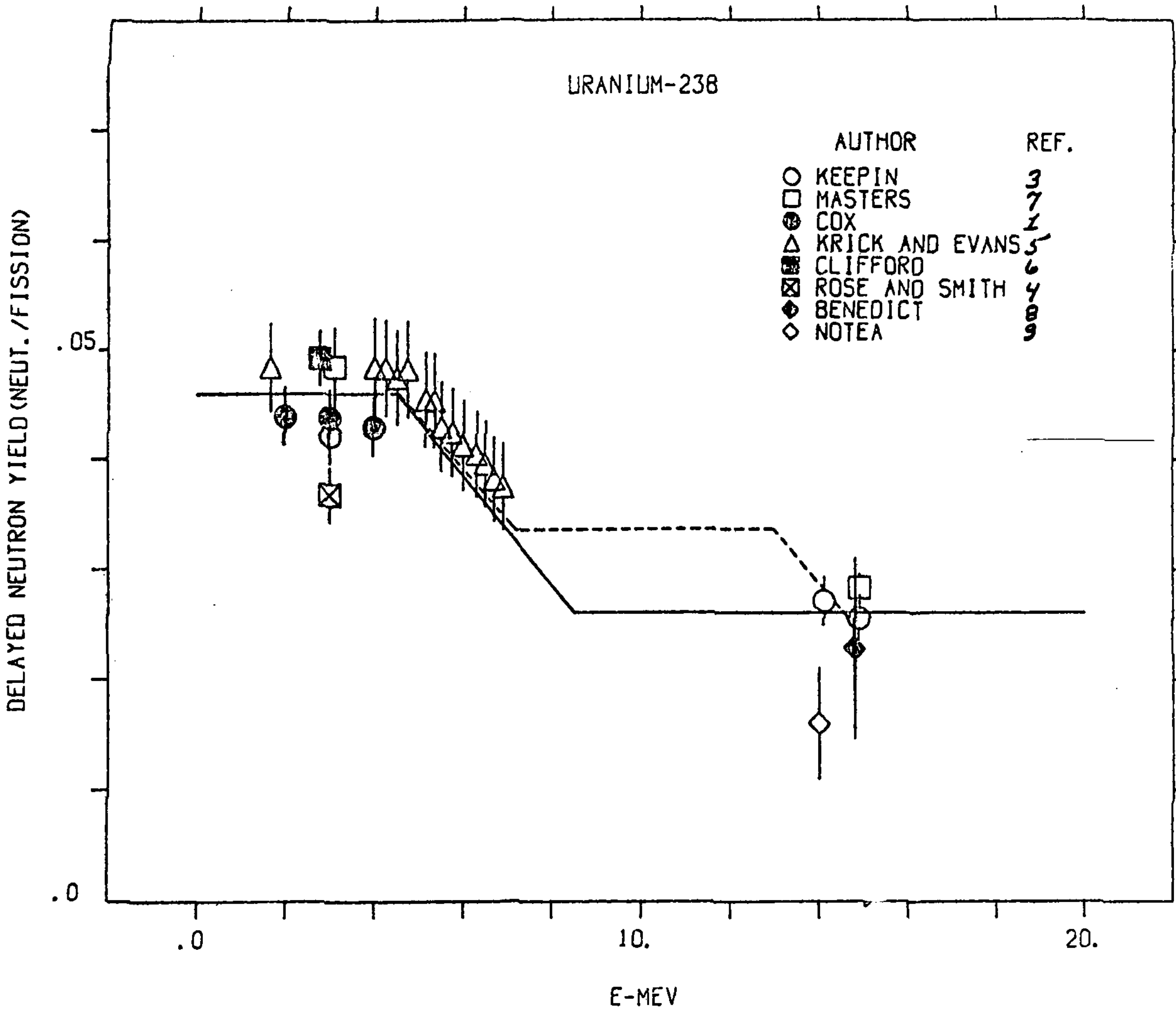
The concern is for the total delayed neutron yield from ^{238}U fission induced by neutrons having energies of interest in fast reactor systems (i. e., few keV to few MeV neutron energies). A precise knowledge of this yield is essential for the interpretation of a wide range of macroscopic measurements (e. g., central-worth measurements and the kinetic behavior of the fast reactor system).

Nature of the discrepancy

The discrepancy is approximately 10% in the magnitude of the total delayed neutron yield from ^{238}U fission induced by neutrons having energies from a few keV to approximately the neutron binding energy.

Status

The status of delayed neutron emission from ^{238}U through 1974 has been extensively reviewed by Cox[1] and by Tomlinson.[2] The situation is outlined in Fig. 1 taken from the evaluation of Cox. Below the neutron binding energy the measured values of Keepin[3] and Cox[1] are in good agreement. The Keepin measurements were made in a pulsed fast critical spectrum while those of Cox used a monoenergetic source of neutrons at several incident energies. The uncertainty assigned to the measured values is approximately 5% and the average of the measured yields is 0.0431 delayed neuts/fission. A third measurement by Rose and Smith gives an even lower result.[4] In the same energy region the results obtained by Krick and Evans,[5] Clifford[6] and Masters et al.[7] are in good agreement with an average yield of 0.0485 delayed neuts/fission. The latter triad of measurements again have assigned accuracies of approximately 5%. Thus there are two sets of measured values each of which is internally consistent well within the assigned uncertainties of approximately 5%. However, the average values from the two sets differ by more than 10%. The discrepancy appears real and represents an uncertainty that has an impact on the fast reactor applications.


URANIUM-238
AUTHOR REF.
KEEPIN 3
MASTERS 7
COX 1
KRICK AND EVANS 5
CLIFFORD 6
ROSE AND SMITH 4
BENEDICT 8
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7. Capture cross sections for structural materials (1 keV—200 keV)

Description of data and their application

Neutron capture in structural materials (steel) is responsible for about 60% of the parasitic absorption in a typical sodium-cooled fast breeder reactor core (most of the rest being due to fission products plus control rods). An accurate knowledge of the capture cross sections of steel components is required in the energy range 1—200 keV for a reliable prediction of neutron absorption. The contribution to parasitic absorption in sodium-cooled fast breeder reactors is highest for Fe, Ni and Cr, somewhat less for Nb, Mo, Mn, and small for V and Ti. The capture cross sections in question have pronounced resonance structure dominated by broad s wave levels with extremely high scattering-to-capture branching ratios (Γ_n/Γ_γ) at the lower end, and by very narrow p and d wave levels at the upper end of the energy range indicated above. Knowledge of the narrow levels and their statistics is required for Doppler effect calculations. Recently the capture cross section of ^{58}Ni has assumed additional importance because it appears that the unexpectedly high production of helium causing excessive swelling of Ni containing steel under neutron irradiation could perhaps be explained by the two-step process ^{58}Ni(n, γ)^{59}Ni(n, α)^{56}Fe.

Status

The most important capture cross sections measurements up to 200 keV performed in recent years are the following:

1. RPI: tank measurements (1100 l liquid scintillator, linac-pulsed neutron source, 100 eV—200 keV) on natural iron, natural nickel and separated isotopes– $^{56-58}$Fe, ^{58,60,61,64}Ni(Hockenbury et al., Nucl. Phys. A163 (1970) 592). Hockenbury et al. reported capture areas for many iron resonances. Stieglitz et al. gave a rather complete parametrization including Γ_γ values for broad levels for ^{51}V, ^{50,52,53,54}Cr, and ^{60}Ni. Preliminary data reduction results on ^{61}Ni were reported in USNDC-11 (1974) by Pandey et al.

2. Karlsruhe: tank measurements (800 l liquid scintillator, pulsed Van de Graaff neutron source, 6 keV—200 keV) on the separated isotopes ^{47}Ti, ^{56}Fe, $^{58,60,61}Ni$ (Ernst et al., 70 Helsinki, vol. 1, p. 633) and $^{50,52,53}Cr$, $^{54,57}Fe$ and $^{62,64}Ni$ (Beer and Spencer, Nucl. Phys. A240 (1975) 29). Detailed sets of resonances parameters including radiation widths were reported for all these isotopes (Ernst et al., 70 Helsinki, vol. 1, p. 633; Fröhner, KFK 2046 (1974) 1 and NBS Spec. Pub. 425, vol. 2, p. 929; Beer and Spencer, NP A240 (1975) 29).

3. Cadarache: total-energy detector measurements (pulsed Van de Graaff neutron source, 15 keV-550 keV) on natural samples of Cr, Mn, Fe and Ni (Le Rigoleur et al., KFK 2046 (1975) 51; 75 Washington, vol. 2, p. 953). No resonance parameters were reported.

References to older measurements can be found in Moxon's review paper, 70 Helsinki, vol. 2, p. 815. Except at the lowest energies these older data did not resolve the resonance structure. Experiments under way include tank measurements on Cr, Fe and Ni at AERE Harwell (200 eV—1 MeV) and work on chromium and ^{56}Fe at ORNL [Macklin, KFK 2046 (1975) 70].

Discrepancies

A comparison of the RPI, KFK and Cadarache capture yield data was made by Le Rigoleur et al. (75 Washington, vol. 2, p. 831). The resonance energies determined at RPI and Cadarache agree well. Those from Karlsruhe are somewhat lower, the $E^{3/2}$ dependence of the shift pointing to a small zero-time or flight path error. More serious are the discrepancies in absolute cross sections. There is reasonable agreement between Cadarache and Karlsruhe, whereas the RPI values are higher, especially between resonances. This is also true for s wave radiation widths and capture areas, RPI values being 10—25% higher than KFK values on the average, with deviations up to almost a factor of 2 in individual cases. This means an uncertainty of some 15—30% in average capture cross sections and statistical parameters.

Error sources

a) Flux determination:

The RPI flux shape was measured with a boron slab detector, i.e., relative to the $^{10}B(n,\alpha\gamma)$ cross section, and normalized with the black resonance technique at 5.19 eV. The extrapolation into the keV region and multiple interactions in the boron slab at low energies could be a problem. Less important error sources are the uncertainty in the reference cross section and errors in the estimation of the black resonance capture yield.

The KFK data were taken relative to gold. The reference cross section used was essentially that of Poenitz which is confirmed by a number of later measurements, among them one at Cadarache with the total-energy detector. Error sources are the need to estimate a ratio of tank efficiencies for gold and the sample under study, and the limited accuracy of the reference cross section.

The Cadarache results were measured with a boron-slab detector or a ^{6}Li glass scintillator calibrated against a standard detector. Errors should be small.

b) Capture detector efficiency:

The main problem with tank measurements is the need to estimate the detection efficiency which is the product of (1) the non-escape probability (intrinsic efficiency) and (2) the pulse-height spectrum fraction above the electronic threshold cutting off background pulses from hydrogen capture, proton recoils etc. Thus the detection efficiency depends on the gamma-ray spectrum, i.e. (1) on the total energy which differs from isotope to isotope and increases slightly with neutron energy, and (2) on the cascade multiplicity which fluctuates from resonance to resonance for a given isotope. The tank pulse-height spectra measured as a function of flight time can be used to correct at least partially for these fluctuations.

The total-energy detector is less affected by spectrum fluctuations (there is a small correction for the detection of more than one cascade photon per event). It is affected, however, by total-energy differences between isotopes, which makes interpretation of the data obtained with isotopic mixtures difficult.

c) Scattered and then promptly scattered neutrons:

For structural materials scattering is much more probable than capture, a least across s-wave resonances. Capture of the scattered neutrons near the sample causes a time-dependent background which is hard to distinguish from the true signal. Calculations at Karlsruhe and Cadarache showed that the effect can be serious across broad s-wave resonances.

d) Sample thickness corrections:

Samples used so far were so thick that multiple-scattering and self-shielding corrections were quite important. (All three groups used similar sample thicknesses). Monte Carlo techniques appear to be the only practicable way to calculate these corrections for resonance cross sections. Intercomparison of computer codes at RPI and KFK ensured that they give consistent results.

Comments and recommendations

a) Extend the measurements at Cadarache to separated isotopes to facilitate comparison with RPI, KFK and forthcoming Harwell results. It would be very desirable to make similar total-energy detector measurements at a high-intensity linac (ORELA) with thinner samples to check on the tank measurements.

b) Tank measurements (e.g. at Harwell and ORELA) should be made with simultaneous registration of pulse-height distributions for each flight-time channel (or at least for the individual resonances) in order to permit corrections for gamma-spectrum fluctuations.

c) Measurements with separated isotopes should be extended to Mn, Mo, Nb, Ti and V.

d) Gold should be used as reference material in tank measurements or for checking purposes in total-energy or Maxon-Rae detector measurements.

e) The possibility of using a large liquid scintillator tank as a total-energy detector should be investigated. This could be a possibility to overcome the problem of gamma spectrum fluctuations.

f) Reduction of resonance capture yields to capture cross sections and accurate Γ_γ determination is only possible if fully parameterized total-cross-section data (level spins, neutron widths) are available. It is absolutely mandatory that all high-resolution capture measurements are supplemented by high-resolution total cross section measurements showing as many as possible of the narrow p- and d-wave levels. The status of Ni data, especially for the main isotope ^{58}Ni, could be much improved if such total cross section results were available. Transmission data in the pipeline (ORELA) should be processed as fast as possible following the example of the ^{56}Fe analysis reported by Pandey et al. (75 Washington, vol. 2, p. 748).

F. Fröhner
July, 1975

8. Γ_γ for 2.85 keV resonance in ^{23}Na

Description and application

Sodium is the primary coolant currently in most current fast breeder reactor systems. In a moderate fast spectrum, primary neutron absorption and gamma-ray production occur predominantly in the neutron energy region below 100 keV where capture is dominated by the contribution from the resonance at 2.85 keV. An accurate knowledge of the capture cross section in this region is necessary for estimating neutron absorption and subsequent gamma-ray heating. A prerequisite to this is a precise value for the total radiation width of the 2.85 keV resonance.

Nature of discrepancy

Direct measurements of Γ_γ have resulted in the following values: 0.47 eV,[1] 0.60 eV,[2] and 0.35 eV.[3] No explanation for these discrepancies has been suggested. However, Γ_γ can also be inferred from the observed resonance parameters if it is assumed that the entire thermal neutron capture cross section is due to the tail of the 2.85 keV level. From an analysis of their total neutron cross section data, Seltzer and Firk[4] have inferred a value of $\Gamma_\gamma = 0.34$, thus suggesting that the value 0.35 eV due to Friesenhahn is correct.

Status

Several measurements of the capture spectrum of the 2.85 keV resonance have been attempted in an effort to determine if the assumption of Seltzer and Firk, that the thermal capture arises completely from the 2.85 keV region is valid. Unpublished data of Chrien et al. indicated a resonance spectrum different from thermal capture, while an unpublished measurement of Rae et al. showed a similar spectrum. A new measurement has been completed at Argonne National Laboratory.[5] All but the extremely weak transitions observed in thermal spectrum can be identified in the new resonant spectrum. Within statistics the two spectra are identical. The new measurement together with the analysis of Seltzer and Firk indicate that with high confidence the reported values of 0.47 and 0.60 can be rejected.

Comments and recommendations

In view of the importance of this parameter to current breeder reactor concepts, a new effort is suggested to confirm directly and to improve the precision of the value $\Gamma_\gamma = 0.34$ eV indicated above. The primary limitation in earlier measurements was correction for multiple scattering of incident neutrons in the 2.85 keV resonance where $\Gamma_n = 308$ eV. Neutron time-of-flight spectrometers with very much improved intensity are now available and measurements are feasible with much thinner samples than was possible in previous measurements.

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H. E. Jackson

9. $\overline{\nu}_p(E)$ of ^{235}U and ^{239}Pu in the 1-keV to 14-MeV region

a. $\overline{\nu}_p(E)$ of ^{235}U

Description of data and its application

Average prompt neutron yield per fission, $\overline{\nu}_p$, of ^{235}U in the energy region of 1 keV to 15 MeV. The data are important in calculations of reactor peoperties. Specific reasons for the requests of data listed in WRENDA 75 are as follows: a) needed as a crosscheck with other isotopes, b) for critical assemblies, and c) for fast reactor calculations.

Nature of discrepancy

(a) Discrepancy amounts to ± 1% at 5 MeV and ± 2% at 400 keV among the different evaluated data.

(b) Recent data show fine structures below about 1 MeV, but details are not yet definite.

Status

(i) Recent measurements:

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2) M. V. Savin, Yu A. Khohlov and V. N. Ludin, ibid. 4 (1973) 63.

3) F. Käppeler and R. E. Bandl, Nuclear Cross Sections and Technology, NBS Special Pub. 425, Vol. 1 (1975) 549.

4) E. A. Seregina, P. P. D'yachenko and B. D. Kuz'minov, Soviet Atomic Energy 37 (1975) 1282

(for other references see Manero and Kohshin (1972) in the following)

(ii) Recent evaluations:

1) W. G. Davey, Nucl. Sci. Eng. 44 (1971) 345.

2) D. S. Mather and P. F. Bampton, AWRE 055/71 (1971).

3) R. L. Walsh and J. W. Boldeman, AAEC/TM 574 (1971).

4) F. Manero and V. A. Konshin, INDC(NDS) 34G (1972).

5) B. Schatz, KFK 1629 (1973).

6) L. I. Prokhorova, V. P. Platonov and G. N. Smirenken, INDC (CCP) 91/U (1976).

7) J. W. Boldeman, J. Frehaut and R. L. Walsh, submitted for publication in Nucl. Sci. Eng.

(iii) Measurements in progress:

1) R. E. Howe and T. W. Phillips (LLL), ERDA/NDC-3/U (1976): Measurement of $\bar{\gamma}$ for ^{235}U in the MeV region ($E_n \leq 25$ MeV).

Comments and recommendations

(a) If a highest accuracy of 0.5% as requested in WRENDA 75 is concerned, the data are discrepant in the all region of energy.

(b) Aspect of the fine structure below about 1 MeV should be clarified by further measurements.

(c) Roughly speaking, for the application where a fine or local structure in a small energy range is not important, most recent evaluation could at least provide the data with accuracy of the order of 2% for the region of 0.1 to 15 MeV.

(d) A review paper by Tsukada is attached in appendix 1.

K. Tsukada and T. Fuketa
(Japan)

b. $\bar{\nu}_p$ (E) of ^{239}Pu

Description of data and its application

Average prompt neutron yield per fission, $\bar{\nu}_p$, of ^{239}Pu in the energy region of 1 keV to 15 MeV. The data are important in calculations of reactor properties. Specific reasons for the requests of data listed in WRENDA 75 are as follows: a) highest priority for fast reactor calculations, and b) for critical assemblies.

Nature of discrepancy

(a) Discrepancies among relatively recent evaluated data amount to about 2% around 5 and 15 MeV.

(b) There seems to exist fine structure below 2 MeV, though it is not yet definite.

Status

(i) Recent measurements:

1) N. P. Kolosov, B. D. Kuz'minov, A. I. Sergachev and V. M. Surin, Soviet Atomic Energy 32 (1972) 92.
2) K. E. Bolodin et al., ibid. 33 (1973) 1045.
3) R. L. Walsh and J. W. Boldeman, Annals Nucl. Sci. and Eng. 1 (1974) 353. (for other references see Manero and Konshin (1972) in the following)

(ii) Recent evaluations:

1) W. G. Davey, Nucl. Sci. Eng. 44 (1971) 345.
2) B. Hinkelman, B. Krieg, I. Langer, J. J. Schmidt and D. Woll, KFK 1340 (1971).
3) R. L. Walsh and J. W. Boldeman, AAEC/TM 574 (1971).
4) F. Manero and V. A. Konshin, INDC(NDS) 34G (1972).
5) R. E. Hunter, L. Stewart and T. J. Hirons, LA 5172 (1973).
6) L. I. Prokhorova, U.P. Platonov and G.N. Smirenken, INDC (CCP) 91/U (1976).

Comments and recommendations

(a) The data measured by Soleilhac et al. (1969) agree with the recommended curve by Manero and Konshin (1972) almost within their measured accuracy of 0.5% up to 15 MeV. This apparently fulfills the request of measurement within 1% accuracy, but discrepancies among the recommended values by Manero and Konshin (1972), Walsh and Boldeman (1971), and Hunter et al. (1973) in 2.5—5 MeV and above 11.5 MeV remain to be solved.

(b) If a highest accuracy of 0.5% as requested in WRENDA 75 is concerned, the data are still unsatisfactory in the full energy range.

(c) Aspect of the fine structures below 2 MeV, if it exists, should be clarified by further measurements.

(d) A review paper by Tsukada is attached in Appendix 1.

K. Tsukada and T. Fuketa
(Japan)

10. Parameters for capture in Ni-59

Description of the data and their applications

The absorption of neutrons by nickel isotopes is of importance in fusion reactors because of the high rate of helium and hydrogen production through (n,α) and (n,p) reactions. Ni-59, formed by neutron capture, has relatively high cross sections and is of interest. Thermal cross sections are available with high precision, and resonance parameters are now available from ORELA.

Nature of discrepancy

Rather wide variations in thermal (n,α) cross sections have been reported. The values for the parameters of the 203.4 eV resonance are not self-consistent, which raises questions on the agreement between resonance and thermal values.

Status

Recent (n,α) measurements at thermal are as follows:

$\sigma = 13.7 \pm 1.2$ barns	(Eiland and Kirouac) NSE 53, 1 (1974)
$\sigma = 18.0 \pm 1.6$	(Werner and Santry) NSE 56, 98 (1974)
$\sigma = 22.3 \pm 1.6$	(McDonald and Sjostrand) Atomkernenergia (submitted)
$\sigma = 12 \pm 1$	(ORNL) ERDA/NDC-3/U
$\sigma = 13.1 \pm 1.1$ (gs), $0.188 \pm .016$ (2^+, 847 keV)	(Asghar, Grenoble, Private communication

Also at thermal σ (n,p) =

4 ± 1	(McDonald and Sjostrand)
2 ± 0.5	(ORNL) ERDA/NDC-3/U
$1.34 \pm .18$	(gs) (Asghar, Grenoble) Private communi.
≤ 0.3	($5/2^-$, 1095 keV)

For the resonance parameters at 203.5 eV, the situation has been fluid:

$E_o = 203.4 \pm 0.2$ eV	$g = 3/8$; $J = 1$	$\Gamma = 13.3 \pm 0.2$
$\Gamma_n = 8.5 \pm 0.15$ eV	$\Gamma_\gamma = 4.0 \pm 0.6$ eV	
$\Gamma_\alpha = 0.5 \pm 0.03$	$\Gamma_p = 0.063 \pm 0.066$	

(ORNL in ERDA/NDC-3/U)

This set gives a thermal absorption cross section which is $\approx 102 \pm 13$ barns as compared to a measured value of 87 ± 6 (also ORNL). However, Harvey (p.c. October 4, 1976) advises that a recalculation of the multiple scattering effect has reduced Γ_γ from 4.0 ± 0.6 to 3.0 ± 0.4 eV. This adjustment gives a good thermal absorption, but makes the parameters internally inconsistent since $\Gamma_n + \Gamma_\gamma + \Gamma_\alpha + \Gamma_p = 12.06 \pm 0.4$ eV vs the measured 13.3 ± 0.2. The problem is thought to be in the Γ_n value.

Comments and recommendations

The thermal capture values are probably consistent, at least for (n,α) at about 11 to 12 barns. Asghar reports (p.c. September 1976) that he has rerun the sample of McDonald and Sjostrand and gets a value 1/2 of their reported result. This is due to an error in the Li-6 monitor they used. If we reduce their values by a factor of 2 we get agreement with ORNL and Grenoble for both (n,p) and (n,α) cross sections. Then only the Werner-Santry result would be discrepant.

The resonance neutron width at 203.4 may be incorrect due to a poor determination of sample thickness. This is a problem which has plagued previous ORNL measurements. The recommendation is to fabricate a sample with a better-determined Ni-59 content.

R. E. Chrien
September, 1976

11. Neutron-induced subthreshold fission in Th-232

Description of the data and their application

A number of measurements have been made on the thermal fission cross section of Th-232 using reactor irradiations. An epithermal measurement has been made using the Rensselaer 75 ton lead slowing down time spectrometer, which had been previously used to measure subthreshold fission in U-238. These measurements are important in two ways: 1) for an understanding of the parameters for the 2-humped fission barrier model, and 2) for the behavior of reactors using thorium to breed U-233 fuel.

Nature of the discrepancy

Early measurements using reactor beams and various detection schemes have varied widely, as indicated in the table quoted below. The most recent measurement by Asghar [NP A259 (1976) 423] was carried out in a very clean thermal beam, at Grenoble, using a neutron guide tube to eliminate γ-ray and fast neutron backgrounds. Previous measurements have used Cd-difference methods to do this. Asghar reports an upper limit of 4 μb, of which a substantial fraction-- 1/2, could be accounted for by transmutation of the Th-232 into U-233. At RPI, the epithermal data are fit to a 1/v function which gives a thermal cross section of 95 ± 30 μb. The older reactor measurements fall in between the Grenoble and RPI values.

Status

A summary of known measurements is as follows (at thermal):

a. Block et al., RPI, $\sigma = 95 \pm 30$ μb
(extrapolation) ERDA/NDC/-3/U

b. Asghar et al., Grenoble $\sigma \leq 4$ μb
Nuc. Phys. A259, 423 (1976)

c. Korneev et al., USSR $\sigma = 60 \pm 20$ μb
JETP 10, 29 (1960)

d. Neve de Mervegnies, del Marmol, Mol 48 ± 6 μb
Washington Conf. 1968; J. Inorg. Nucl. Chem. 35, (1973) 4323

e. Ghiorso and van Winkle, < 10 μb
TID 5223 II (1952)

Comments and recommendations

Sample purity is probably the main problem here. The most obvious suggestion is to take the RPI thorium chamber to a reactor, such as HFBR, to check the thermal cross section. The measurements listed above can be seriously affected by the presence of even a few parts/billion of a fissile material such as U-233 or U-235. The irradiation history of each sample used above should be verified for possible U-233 production.

R. E. Chrien

12. AM-241(n,f)

Description of data and its application

Fission cross section of AM-241 in the energy range 50 eV to 100 keV. Am-241 is one of the most important transplutonium isotopes produced in the fission reactor fuel cycle. The Cm-242 produced by neutron capture is particularly important as a neutron source in irradiated fuel.

Nature of the discrepancy

There is a major discrepancy in the available data between the resolved resonance region (50 eV) and 100 keV. The data divide into two groups up to a factor 40 apart. The main data in the upper group are the bomb shot measurements of Seeger et al [Nucl. Phys. A96, 605 (1967)] which give values varying between 0.5 and 1.5 barns from 50 eV to 20 keV. Above 20 keV the values fall rapidly to less than 20 mb above 50 keV. The data of Seeger et al are supported by the unpublished measurements of Migneco et al. below 3 keV. In the lower group there are the data of Bowman et al. [Phys. Rev. 137B, 326 (1965)] which give values between 0.1 and 0.3 barns below 6 keV and the measurements of Shpak et al. [JETP Letters 10, 175 (1969)] which give values of 15 to 30 mb between 8 and 100 keV.

Status

There are no recent measurements on the Am-241 fission cross section but experiments are now in progress or are planned at Karlsruhe (in association with ISPRA), Geel, Harwell, and Livermore. Preliminary data from Livermore (UCID-17324) and Harwell (Gayther and Thomas, priv. comm.) suggest that the data in the low group are correct.

Conclusions and recommendations

There is a need for more measurements on this cross section. The experiments are difficult because of the low cross section and high specific α-activity of Am-241. The measurements in progress will probably solve the major discrepancies but a lot of work is probably necessary before the most stringent requests in WRENDA-75 for a ± 3 to 10% accuracy are satisfied.

M. G. Sowerby

APPENDIX

Review on the Average Prompt Neutron Yield per Fission of ^{235}U and ^{239}Pu in the Neutron Energy Range of 1 keV to 15 MeV

Kineo Tsukada

A. $\bar{\nu}_p$ of ^{235}U

Concerning the evaluation on the average prompt neutron yield per fission $\bar{\nu}_p$ of ^{235}U, papers by Davey (1971)[1], Walsh et al. (1971)[2], Mather et al. (1971)[3], Manero et al. (1972)[4] and Schatz (1973)[5] are the main works published since 1971, which are referred to CINDA 75. Newer papers on the measurement of $\bar{\nu}_p$ by Käppeler et al. (1975)[11], Frehaut et al. (1973)[12] and Savin et al. (1973)[13] are not taken up in the above papers on the evaluation. The above mentioned papers are reviewed in the following.

A-1) Work on the evaluation by Manero et al. (1972)[4]

In this paper, the previous evaluation works of Ref. 1) - 3) were discussed, in addition to that the all available measured data were taken into account. The oldest reference on the measurement was of 1945. Measured data sets published after 1969 with relatively high accuracy were referred to papers by Soleilhac et al. (1969)[6]*, Soleilhac et al. (1970)[7], Savin et al. (1970)[8], Nestrov et al. (1970)[9] and Boldeman et al. (1970)[10].

A "convexity" in the energy dependence of $\bar{\nu}_p(^{235}U)$, which was first pointed out by Blyumkina et al. (1964)[22], had been recognized by many measurements as a step-like structure or a fine structure. But, Walsh et al. (1971)[2] were negative to the existence of such a structure.

Since the individual works adopted different standard values of the average prompt neutron yield of spontaneous fission of ^{252}Cf ($\bar{\nu}_p^{sp}$(Cf)), Manero et al. made renormalization of those data by adopting

$$\bar{\nu}_p^{sp}(^{252}Cf) = 3.756 \pm 0.012$$

from Hanna et al. (1969)[21].

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* The original data in Ref. 6) was later corrected by its authors as mentioned in Ref. 4). The corrected value are adopted in the present review.

[Note] In the figures of the present review, all values are normalized to $\bar{\nu}_p^{sf}$ (^{252}Cf) = 3.756.

The analyses were made on the all available data and on the data with the energy resolution of the order of 50 keV, where the latter data mainly consisted of those reported after 1961. Since there was no appreciable difference between the two analyses, the only data of the latter were considered finally. The result was expressed by the following equations.

(i) $\bar{\nu}_p(E) = 2.40591 - 0.01368E + 2.45575E^2 - 10.86137E^3 + 20.80908E^4 - 20.57858E^5 + 10.99438E^6 - 3.01762E^7 + 0.33403E^8$

for the energy region of thermal to 2.05 MeV, with the standard deviation of 0.00135.

This equation was derived from 128 data points.

(ii) $\bar{\nu}_p(E) = 2.20576 + 0.339328E - 0.087402E^2 + 0.014487E^3 - 0.76989(10^{-3})E^4$

for the energy region of 2.05 to 7.5 MeV, with the standard deviation of 0.00061.

This equation was derived from 44 data points.

(iii) $\bar{\nu}_p(E) = 2.49238 + 0.135491E$

for the energy region of 7.5 to 15 MeV, with the standard deviation of 0.00129.

This equation was derived from 21 data points.

A-2) Work on the evaluation by Davey (1971)[1]

This paper dealt with the measured data published by 1969. $\bar{\nu}_p^{sf}$ (^{252}Cf) = 3.756 was adopted as the standard value. Effects of the thresholds of (n,n'f) and (n,2nf) reactions were taken into account at the fitting to the data. An effect of (n,n'f) reaction showed up remarkably at about 7 MeV, but an effect of (n,2nf) reaction was not so remarkable. Above 1.36 MeV, the fittings were made to the only data by Soleilhac et al. (1969)[6] and to the all data published by 1969. Since there was no essential difference between the two fittings, the fitting to the data by Soleilhac et al. was adopted. Below 0.5 MeV, many data so scattered that the evaluation could not be made. But, there seemed to exist steep increase of $\bar{\nu}_p$ at about 0.4 MeV and 1.1 MeV.

The authors of Ref. 1) pointed out that, according to the channel theory of nuclear fission, $\bar{\nu}_p$ is constant independently of the incident neutron energy when only one channel is open. As the channels open, $\bar{\nu}_p$ increases stepwise; and $\bar{\nu}_p$ increases linearly with the energy at an extremity of high channel density. But, $\bar{\nu}_p$ decreases at the thresholds of (n,n'f) reaction etc. The nuclear fission may assume different aspects for s-, p-wave and higher partial wave neutrons. The results of the evaluation were as follows:

$\bar{\nu}_p(E) = 2.409 + 0.1077E$	0.50 to 3.50 MeV
$\bar{\nu}_p(E) = 2.267 + 0.1488E$	3.50 to 5.06 MeV
$\bar{\nu}_p(E) = 2.012 + 0.1992E$	5.06 to 7.56 MeV
$\bar{\nu}_p(E) = 2.491 + 0.1358E$	7.56 to 11.50 MeV
$\bar{\nu}_p(E) = 2.477 + 0.1365E$	11.50 to 15.00 MeV

A-3) Work on the evaluation by Walsh et al. (1971)[2)]

In this paper, it was derived that

$$\bar{\nu}_p(E) = 2.416 + 0.107E\ , \qquad \text{for}\quad E = 0 - 2\ \text{MeV},$$

from the measured data by Boldeman et al. (1970)[10)], where any structure was not seen. Ajitanand and Boldeman (1970)[23)] also showed that the measured values of average total fragment kinetic energy $\bar{E}_K$ were constant for the range of thermal to 1 MeV, and there was no indication of a structure.

For the energy range of 1.36 to 5 MeV,

$$\bar{\nu}_p(E) = 2.373 + 0.129E$$

was derived from the measured data by Soleilhac et al. (1969)[6)]. In both cases, $\bar{\nu}_p^{sp}(^{252}Cf) = 3.782$ was adopted. A change occurred at 1.95 MeV in the slope of the energy dependence of $\bar{\nu}_p$. Walsh et al. pointed out that this energy has relation to the pairing energy of ^{235}U.

A-4) Work on the evaluation by Mather et al. (1971)[3)]

This paper dealt with the all measured data reported before 1971. $\bar{\nu}_p^{sp}(^{252}Cf) = 3.7567$ was adopted as a standard value. Below 1 MeV, especially in the region of 300 to 500 keV, a spread in the measured values of $\bar{\nu}_p$ was remarkable, which was attributed to the existence of a fine structure and to the discrepancy in energies and resolutions of measured points among different experiments. Accordingly, they averaged all measured data with 50 keV width in the region of 0 - 2 MeV. In Fig. 1, mark ⊙ with error bar indicates the averaged value, and a broken line simply connects these marks. Instead of this simple connection, in Ref. 3), a fitting to those averaged values was made by using a cubic spline fitting computer code. In the range above 1.75 MeV, general shape of $\bar{\nu}_p(E)$ was obtained from the measured data by Soleilhac et al. (1969)[6], while the absolute values were obtained by taking average of the fitting parameters which were respectively derived from the fittings to the three groups of measured data: the data by Soleilhac et al. (1969)[6], by Savin et al. (1970)[10], and by others. The results were divided into four energy region:

$\bar{\nu}_p(E) = 2.3829 + 0.1262E$	1.75 to 3.69 MeV
$\bar{\nu}_p(E) = 2.3453 + 0.1364E$	3.69 to 4.918 MeV
$\bar{\nu}_p(E) = 2.0497 + 0.1965E$	4.918 to 7.101 MeV
$\bar{\nu}_p(E) = 2.4715 + 0.1371E$	7.101 to 15.0 MeV

A-5) Work on the evaluation by Schatz (1973)[5]

This paper includes the measured data reported from 1961 to 1970, except for the data by Boldeman et al (1970)[10]. $\bar{\nu}_p^{sf}(^{252}Cf) = 3.756$ was adopted as a standard. It was pointed out by Leachman (1956)[24] that the energy dependence of $\bar{\nu}_p$ is expected to be linear from the fact that the average kinetic energy of the fragments does not depend on the excitation energy of the fissioning nucleus. Blyumkina et al. (1964)[22] attributed the irregularity in the energy dependence of $\bar{\nu}_p$ to a transfer from a fission channel to the other one, e.g. from s-wave neutron to p-wave neutron channel, in connection to the irregularity of the average kinetic energy of fission fragments. Validity of this assumption is not clear yet at present. The result was given as follows:

$(E) = 2.4003 + 0.1245E$	1.5 to 4.8 MeV
$(E) = 2.509 + 0.136E$	7.5 to 10.5 MeV
$(E) = 2.372 + 0.145E$	11.5 to 15 MeV

(There are 10 straight line fits dividing the energy region of 1.5 to 15 MeV into 10 sections in the same paper.)

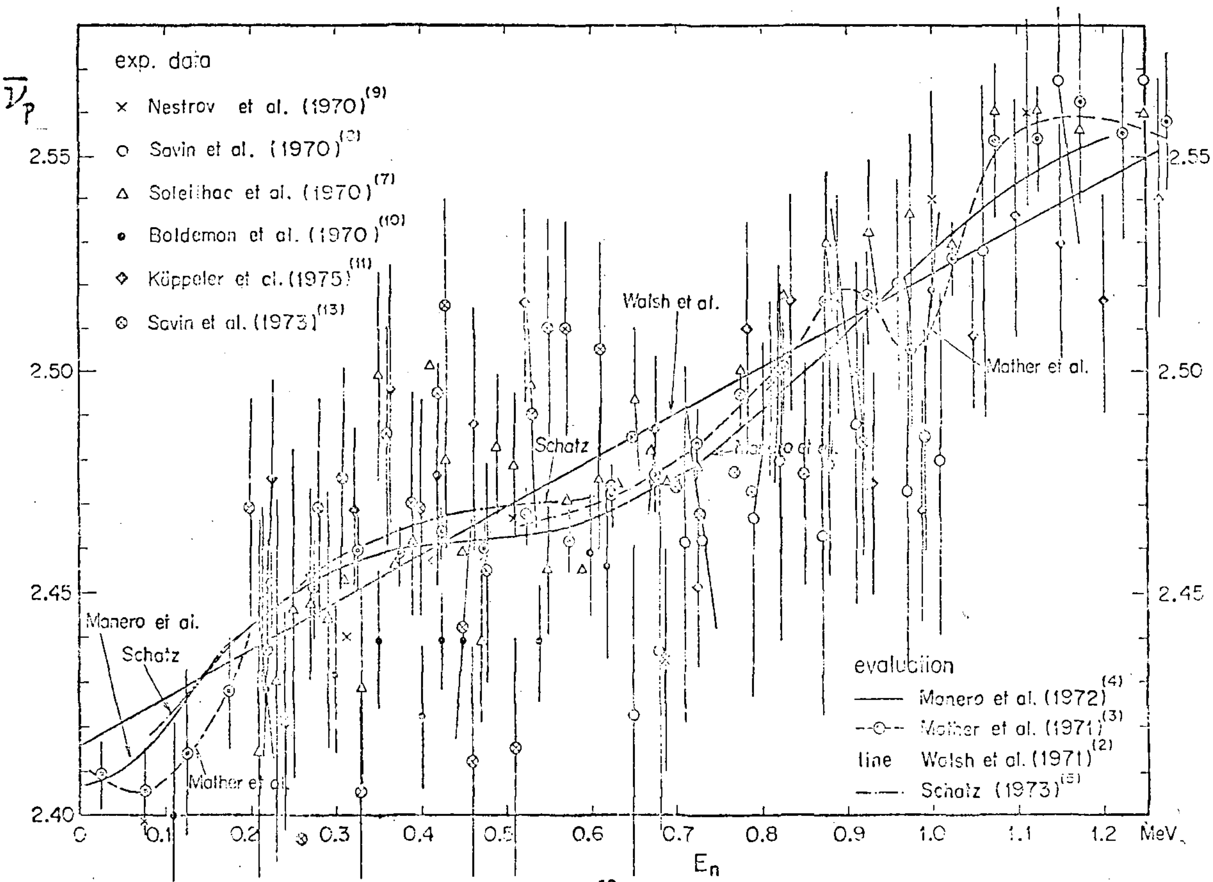

Fig. 1 $\overline{\nu}_p$ of U-235 ($\overline{\nu}_p^{sp}$(Cf-252) = 3.756) where $\bar{\nu}(E)$ means total neutron yield $\bar{\nu}_t(E) = \bar{\nu}_p(E) + \bar{\nu}_d(E)$. The value of the delayed neutron yield $\bar{\nu}_d$ was estimated in Ref. 5) based on some measured data as follows:

$$\bar{\nu}_d = 0.0158 \pm 0.0005 \qquad \text{(thermal)}$$
$$\bar{\nu}_d = 0.018 \pm 0.002 \qquad \text{(below 10 MeV)}$$
$$\bar{\nu}_d = 0.0095 \pm 0.0008 \qquad \text{(above 10 MeV)}$$

Ref. 5) gives smooth curve for $\bar{\nu}_p$ value below 1.5 MeV, which is partly shown in Fig. 1 by a broken line, and the other part agrees to the result by Manero et al.

A-6) <u>Work on the measurement by Käppeler et al. (1975)[11]</u>

Principal aim of this new work was in the measurement of the energy dependence of $\bar{\nu}_p$, and the absolute measurement was not intended. The systematic error of the data was estimated to be $\leq$ 0.7 %. The measurement was made with 50 keV steps and an average energy resolution of 3.3 % in the energy region of 0.2 to 1.4 MeV. Deviation from the linearity of $\bar{\nu}_p$ value was about 2 %, which was about 3 times as large as the structure seen in Ref. 4). The result of Ref. 11) is plotted in Fig. 1 with mark ♦ and Fig. 1A with mark ⊙ .

[Note by the present reviewer: The standard value of $\bar{\nu}_p^{sp}$(^{252}Cf) used is not mentioned in Ref. 11).]

A-7) <u>Work on the measurement by Frehaut et al. (1973)[12]</u>

This paper adopted $\bar{\nu}_p^{sp}$(^{252}Cf) = 3.782 as a standard. The measurement was made with energy steps of 0.5 - 1 MeV and with relative accuracy of 1.5 % in the energy region of 1.5 - 15 MeV. The result above 6 MeV showed excellent agreement with that of Soleilhac et al. (1969)[6]. The result below 6 MeV was generally larger than that of Ref. 6), and the difference reached 3 % at around 4 MeV. The result is shown in Fig. 2 with mark ⊕ , but mark ⊕ is omitted wherever mark ⊕ overlap with mark ● which indicates the result by Soleilhac et al.

A-8) <u>Work on the measurement by Savin et al. (1973)[13]</u>

This paper adopted $\bar{\nu}_p^{sp}$(^{252}Cf) = 3.756 as a standard. The measurement was made with energy steps of 20 - 40 keV and with 1 % accuracy in

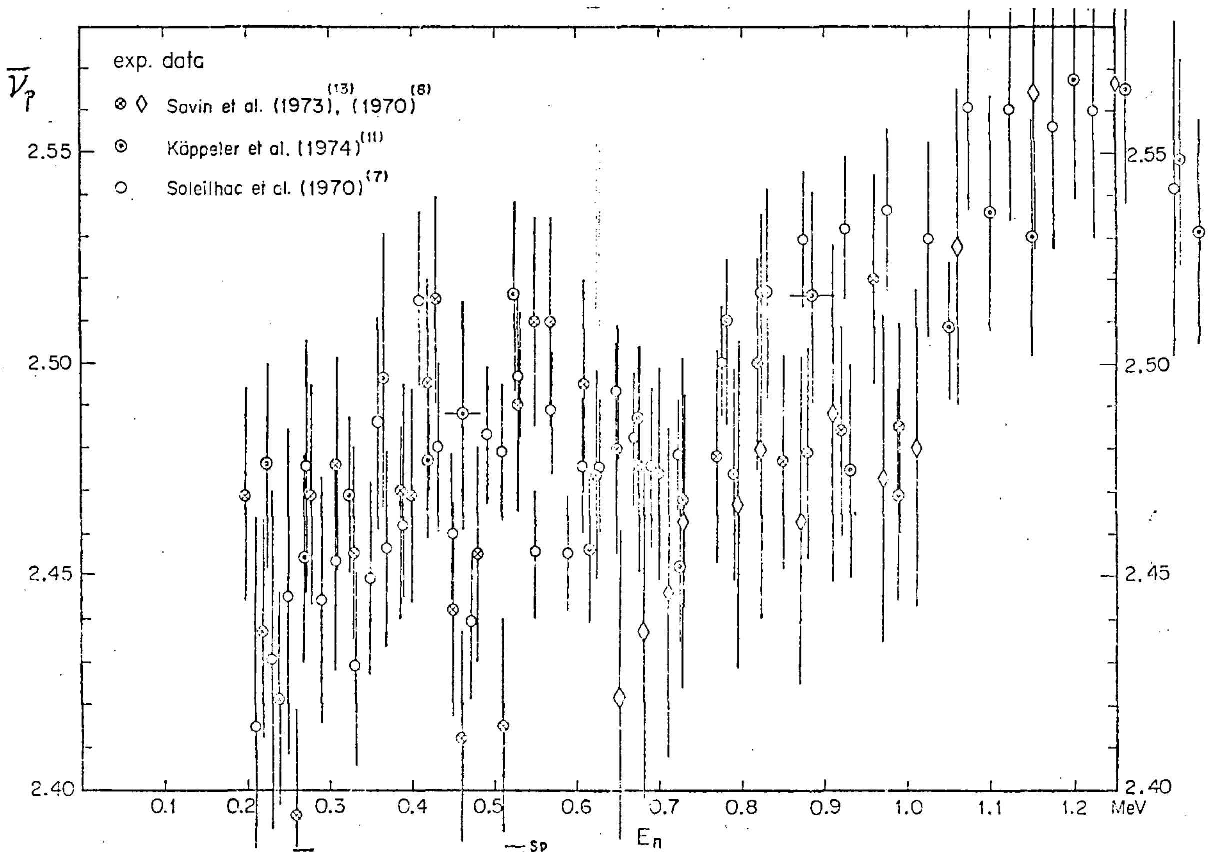

Fig. 1A $\overline{\nu}_p$ of U-235 ($\overline{\nu}_p^{sp}$ (Cf-252) = 3.756 except for Käppeler et al.)

the energy region of 0.20 - 1.0 MeV. The result is plotted with mark ⊗ in Figs. 1 and 1A.

[Comments of the present reviewer]

(i) In comparison of the papers 1) - 5) on the evaluation, the results agree generally with each other, except that the result of Davey (1971)[1] is more or less smaller (about 1 % in the maximum) than those of the others in the region of 2.5 - 6.5 MeV, and that Walsh et al. (1971)[2] give a straight line for the energy region below 1 MeV.

(ii) As is shown in Fig. 2, an effect of the threshold of (n,n'f) reaction is clear around 6 MeV, but an expected effect of the (n,2nf) reaction at about 11 MeV is not seen. This is in contrast with the case of ^{239}Pu where an effect of (n,2nf) reaction appears but an effect of (n,n'f) reaction is hardly seen in the plot of $\bar{\nu}_p$ values.

(iii) In Fig. 1, the comparison among the recent measured data since 1970 shows that a spread of the data around 400 keV reaches to $\pm$ 2 %. This seems attributable to the existence of fine structure at that energy region, to the error in incident neutron energy measurements, and to the difference of energy resolutions in different measurements. This is concurrent among the above evaluators except for Walsh et al. (1971)[2]. It seems that there is also a structure at about 1.1 MeV, which could be a step-wise one.

(iv) The measured data by Savin et al. (1970)[8], (1973)[13], Käppeler et al. (1975)[11], and by Soleilhac et al. (1970)[7] are plotted in Fig. 1A. A general aspect of the data seems to show a fair agreement among the different sets of data except for the region of 0.8 - 1.0 MeV. A possible existence of sharp peaks at about 0.42 and 0.53 MeV should be remarked. There might also be a peak around 0.82 MeV. A scattering of the data is worse at 0.8 - 1.0 MeV.

(v) In WRENDA 75, the data for $\bar{\nu}_p$ of ^{235}U are requested as follows:

[Energy Range]	[Accuracy]	[Priority]	
25.3 MV - 3.00 MEV	1.0 %	1	
25.3 MV - 2.50 MEV	0.5 %	2	
- 15.0 MEV		1	(accuracy 1 % above 1 keV)
5.00 KEV - 10.0 MEV		1	(accuracy 1 % from 0.1 - 0.8 MeV)

First of all, the aspect of the above mentioned fine structure should be clarified. Even with an energy resolution of say 10 %, to measure $\bar{\nu}_p(E)$ with accuracy better than 1 % is a quite severe request under the present state of art.

B. $\bar{\nu}_p$ of ^{239}Pu

Major reports on the evaluation of $\bar{\nu}_p$ value of ^{239}Pu published since 1971 are those by Davey (1971)[1], Walsh et al. (1971)[2], Hinkelman et al. (1971)[14], Manero et al. (1972)[4], Hunter et al. (1973)[15] and Konshin et al. (1973)[16], which are referred to CINDA 75. Newer papers on the measurement of $\bar{\nu}_p$ by Kolosov et al. (1972)[18], Bolodin (1973)[19] and Walsh et al. (1974)[20] are not taken up in the above papers on the evaluation. The above mentioned papers are reviewed in the following.

B-1) Work on the evaluation by Manero et al. (1972)[4]

In this paper, the previous evaluation works of Ref. 1), 2), and 14) were discussed, in addition to that all available measured data were taken into account. The oldest reference on the measurement was of 1954. Measured data sets published after 1969 with relatively high accuracy were referred to papers by Soleilhac et al. (1969)[6]*, Soleilhac et al. (1970)[7], Savin et al. (1970)[8], Nestrov et al. (1970)[9], Mather et al. (1970)[17], and Boldeman et al. (1970)[10]. The data by Conde et al. (1970)[25] was omitted since the energy dependence of $\bar{\nu}_p$ was not measured in Ref. 25). Because the individual works adopted different standard values of $\bar{\nu}_p^{sp}(^{252}Cf)$, Manero et al. made renormalization of those data by adopting

$$\bar{\nu}_p^{sp}(^{252}Cf) = 3.756 \pm 0.012$$

from Hanna et al. (1969)[21].

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* The original data in Ref. 6) was corrected later by its authors as mentioned in Ref. 4). The corrected data are adopted in the present review.

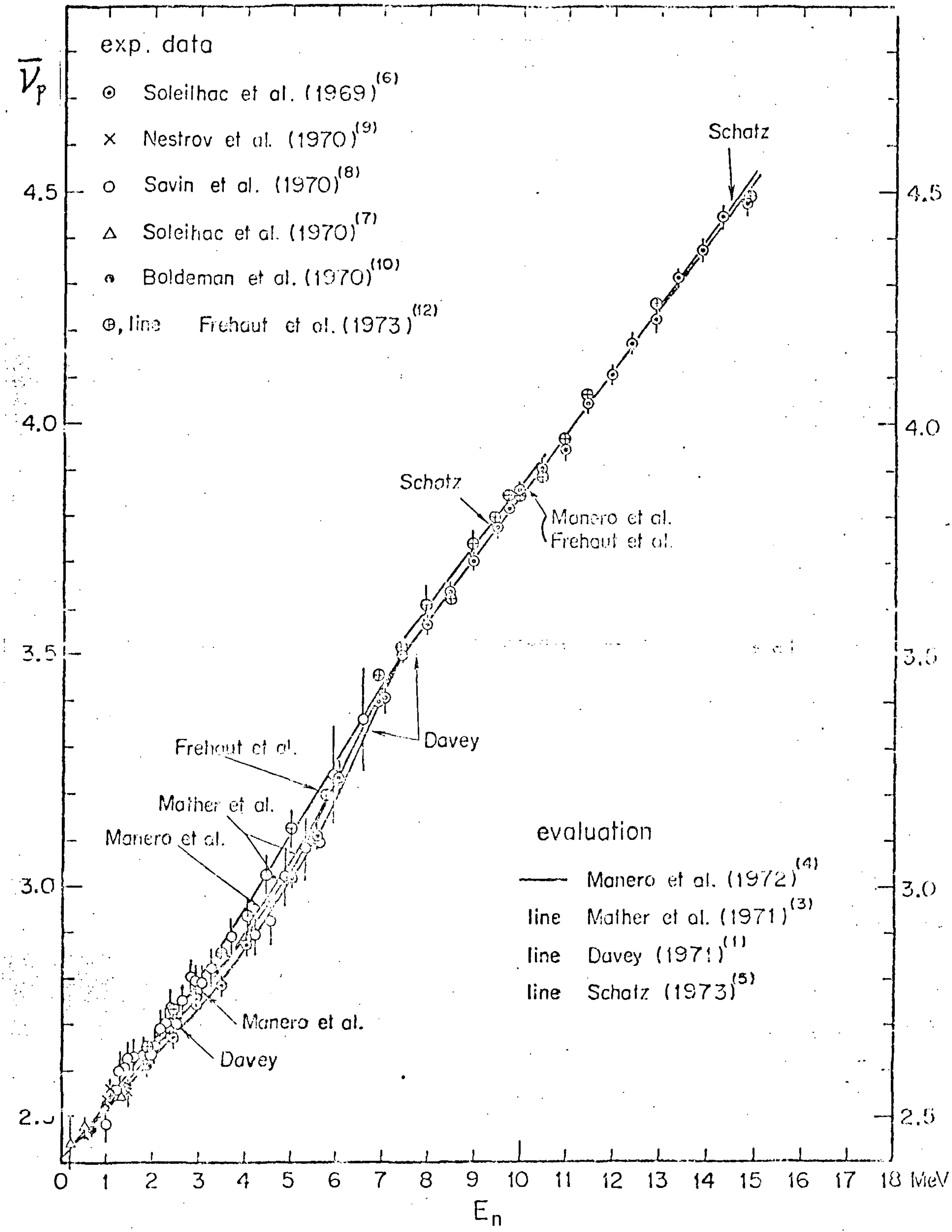

Fig. 2 $\overline{\nu}_p$ of U-235 ($\overline{\nu}_p^{sp}$ (Cf-252) = 3.756)

[Note] In the figures of the present review, all values are normalized by using $\bar{\nu}_p^{sp}(^{252}Cf) = 3.756$.

The results of anlaysis by using of the all data reported from 1954 to 1972 are given as follows.

(i) $\bar{\nu}_p(E) = 2.86999 + 0.09823E + 0.044129E^2 - 0.015334E^3 + 0.0022321E^4 - 0.0001134E^5$

for the energy region of thermal to 3.8 MeV, with standard deviation of 0.00196.
This equation was derived from 103 data points.

(ii) $\bar{\nu}_p(E) = 2.86240 + 0.134784E + 0.34692(10^{-2})E^2 - 0.18820(10^{-3})E^3$

for the energy region of 3.8 to 15 MeV, with standard deviation of 0.00183.
This equation was derived from 43 data points.

B-2) Work on the evaluation by Davey (1971)[1]

This work dealt with the measured data published by 1969. $\bar{\nu}_p^{sp}(^{252}Cf) = 3.756$ was adopted as the standard value. The energy dependence of the measured data was almost linear. Although appreciable change in the slope did not appear in the energy dependence, fitting of equations to the data was made setting a breakpoint at about 11.5 MeV where an effect of (n,2nf) reaction was expected to be remarkable. Although the situation of the data in lower energy region was such that a reliable recommended values were hardly derived, the energy dependence was almost straight and the structure was small, if any. The result was given as follows.

$\bar{\nu}_p(E) = 2.835 + 0.1506E$	1.50 to 5.00 MeV
$\bar{\nu}_p(E) = 2.816 + 0.1560E$	5.00 to 7.50 MeV
$\bar{\nu}_p(E) = 2.866 + 0.1495E$	7.50 to 11.50 MeV
$\bar{\nu}_p(E) = 2.954 + 0.1398E$	11.50 to 15.00 MeV

B-3) Work on the evaluation by Walsh et al. (1971)[2]

In the anlaysis of this work, the measured data reported by 1970 were used. $\bar{\nu}_p^{sf}(^{252}Cf) = 3.782$ was adopted as the standard. Although the measured data in the region of 0 - 5 MeV were fairly well fitted by

$$\bar{\nu}_p(E) = (2.870 \pm 0.003) \pm (0.147 \pm 0.002)E$$

the data at thermal and low energy were larger than the values given by the above equation, which did not intersect the $\bar{\nu}_p$ value of the spontaneous fission of ^{240}Pu at - 6.3 MeV. These problems were solved by fitting the following two equations to the data.

$$\bar{\nu}_p(E) = (2.889 \pm 0.007) + (0.108 \pm 0.014)E \qquad 0 \text{ to } 700 \text{ keV}$$
$$\bar{\nu}_p(E) = (2.861 \pm 0.006) + (0.152 \pm 0.003)E \qquad 700 \text{ keV to } 5 \text{ MeV}$$

Walsh et al. suggested that the break point of the above two straight lines at 700 keV correlated with the pairing energy of ^{239}Pu. This was similar to the case of ^{235}U.

B-4) <u>Work on the evaluation by Hinkelman et al. (1971)[14]</u>

This work dealt with the measured data reported by 1969. $\bar{\nu}_p^{sf}(^{252}Cf) = 3.764$ was adopted as the standard. The result for the total neutron yield was given by the following equations.

$$\bar{\nu}_t(E) = 2.89200 + 0.12791E + 0.00189E^2 - 0.00010E^3 \qquad \text{thermal to } 3.4 \text{ MeV}$$
$$\bar{\nu}_t(E) = 2.81908 + 0.15463E \qquad 3.4 \text{ to } 15 \text{ MeV}$$

To obtain $\bar{\nu}_p$, $\bar{\nu}_d = 0.006 \quad \leq 10$ MeV
$\bar{\nu}_d = 0.013 \quad \geq 10$ MeV

should be subtracted from $\bar{\nu}_t$.

B-5) <u>Work on the evaluation by Hunter et al. (1973)[15]</u>

This work dealt with the measured data reported by 1970, except for the data by Boldeman et al. (1970)[10]. $\bar{\nu}_p^{sf}(^{252}Cf) = 3.748$ was adopted as the standard. The result was given as follows.

$$\bar{\nu}_p(E) = 2.8480 + 0.1502E \qquad 0 \text{ to } 11.5 \text{ MeV}$$
$$\bar{\nu}_p(E) = 3.1216 + 0.1237E \qquad 11.5 \text{ to } 20.0 \text{ MeV}$$

The breakpoint at 11.5 MeV was remarked.

B-6) <u>Work on the measurement by Kolosov et al. (1972)[18]</u>

In this work, $\bar{\nu}_p$ values were obtained by the energy balance from the result of measurements on the distributions of the masses and kinetic energies of the fission fragments. The measurement was made in the energy region of 0 - 1.6 MeV with energy resolution of ± 50 keV. The recommendation by Kolosov et al. is plotted with dotted line in Fig. 3, where $\bar{\nu}_p^{sf}$ (^{252}Cf) = 3.756 was adopted as the standard value.

B-7) Work on the measurement by Bolodin et al. (1973)[19]

$\bar{\nu}_p^{sf}$ (^{252}Cf) = 3.756 was adopted as the standard. Two measurements were made: the first was made in the energy region of 0 - 1.6 MeV with statistical errors of 0.5 - 1 %, and the second in 0.08 - 0.7 MeV with statistical errors of 1 %. There was a possibility that a part of delayed neutrons mixed with the latter measurement. According to the Ref. 19), the spread of the $\bar{\nu}_p$ data in the region of 1.15 - 1.35 MeV is due to the existence of fine structure in the energy dependence, and to the disagreement of neutron energies among the different measurements. Correlations between $\bar{\nu}_p$, the average kinetic energy of fragments $\bar{E}_K$, a parameter for the angular distribution $\overline{K^2}$, and the fission cross section σ_f were noticed at 1.2 - 1.3 MeV. These correlations might originate from an inhomogeneity in the intermediate state density of the fissioning nuclei.

Measured data by Nestrov et al. (1970)[9] are omitted in Fig. 3, because they mis-estimated the content of ^{240}Pu in their sample at one order less than the actual amount according to the Ref. 19).

B-8) Work on the measurement by Walsh et al. (1974)[20]

Walsh et al. made the measurement in the energy region of 0.2 - 1.9 MeV. The result agreed quite well with the data by Boldeman et al. (1972). Walsh et al. also made evaluation for the energy region of 0 - 5 MeV including available measured data by 1972. $\bar{\nu}_p^{sf}$ (^{252}Cf) = 3.724 was adopted. They did not find any fine structure in the low energy region. They gave the following equations as the best discription of the energy dependence of $\bar{\nu}_p$:

$$\bar{\nu}_p = (2.844 \pm 0.007) + (0.112 \pm 0.013)E \qquad 0 \text{ to } 0.78 \text{ MeV}$$
$$\bar{\nu}_p = (2.799 \pm 0.007) + (0.170 \pm 0.003)E \qquad 0.78 \text{ to } 5 \text{ MeV}$$

There are not much differences in $\bar{\nu}_p$ values between the equations of Ref.

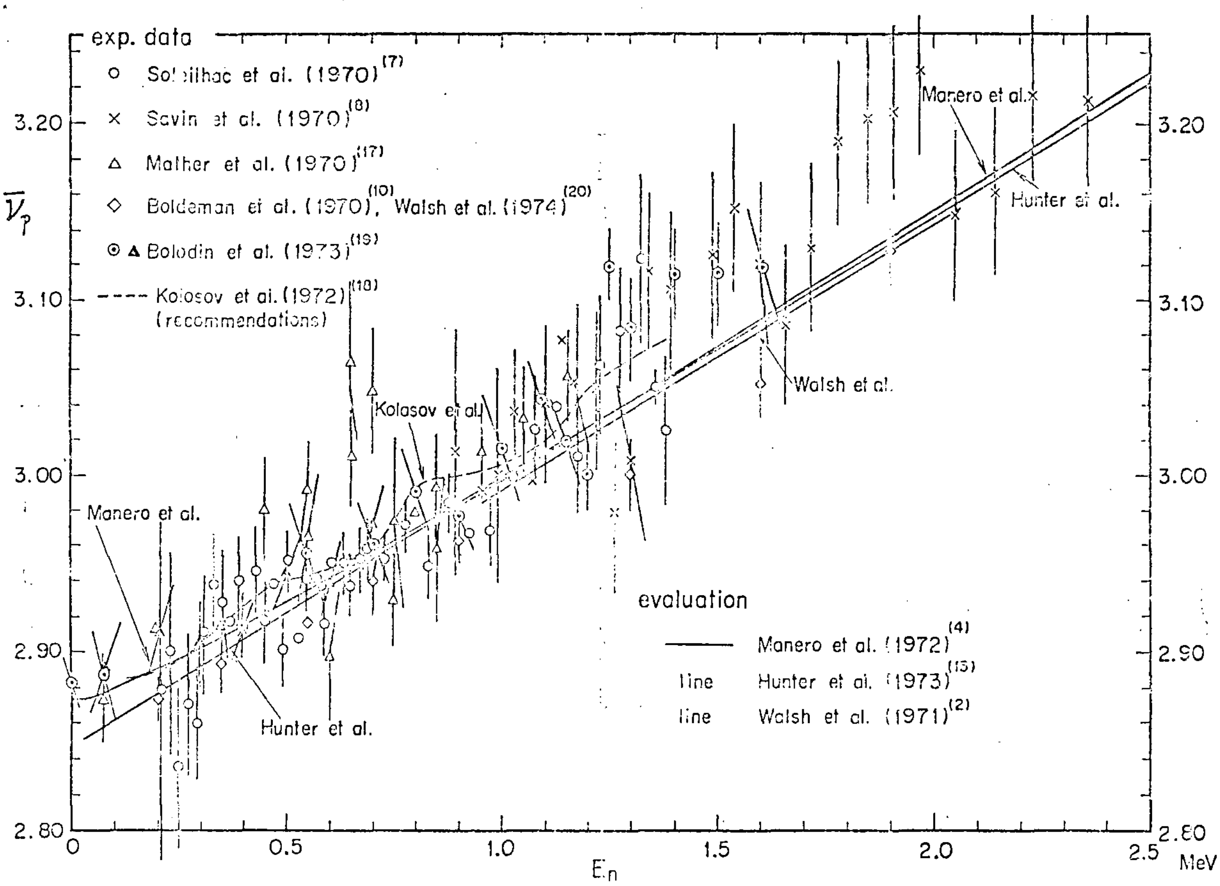

Fig. 3 $\bar{\nu}_p$ of Pu-239 ($\bar{\nu}_p^{sp}$(Cf-252) = 3.756)

20) and Ref. 2) in lower energy side, but the former gives fairly higher $\bar{\nu}_p$ value than the latter in high energy side. From Ref. 20), the difference of 2.3 MeV between the threshold energy (- 1.5 MeV) of ^{239}Pu fission and the energy (0.8 MeV) of the break point of the above two equations corresponds to the excitation energy where a change occurs in the fission fragment angular distribution of ^{239}Pu. This change corresponds also to the pairing energy gap $2\Delta_f$. However, some other authors adopt $2\Delta_f \approx$ 1.5 MeV.

[Comments of the present reviewer]

(i) There are good agreements among the recommended values of Ref. 1), 2), 4), 14) and 15), except that the values by Hinkelman et al. (1971)[14] are larger than those of others below 1.5 MeV and above 12 MeV, and that the values by Hunter et al. (1973)[15] are smaller than others above 12 MeV. Agreement between the values by Walsh et al. (1971)[2] and Manero et al. (1972)[4] is especially good below 2 MeV, but disagreement between these values and the values by Walsh et al. (1974)[20] reaches about 2 % at 5 MeV.

(ii) Referring to Fig. 3, the aspect of the data points of Bolodin et al. (1973)[19] (marks ◎ and ▲) and Savin et al. (1970)[8] (mark ×) seems to suggest the existence of structure in $\bar{\nu}_p(E)$ at E = 1.2 - 2 MeV. There might also be a fine structure in the lower energy region. This is supported by the correlations among $\bar{\nu}_p$ and the other fission data as pointed out by Bolodin et al., and by the result from the energy balance as measured by Kolosov et al.

(iii) There is an indication of the effect of (n,2nf) reaction around 11 - 12 MeV. About this, both Manero et al. (1972)[4] and Hunter et al. (1973)[15] pointed out agreeably, but their recommended values of $\bar{\nu}_p$ disagree with each other considerably, i.e. the value by Hunter et al. is smaller by 1 % than the value by Manero et al. at 15 MeV. The values by Manero et al. mainly depend upon the measured data by Soleilhac et al. (1969)[6], and to the contrary, Hunter et al. used many other data around 15 MeV, which were generally smaller than those of Soleilhac et al. and associated with relatively large errors.

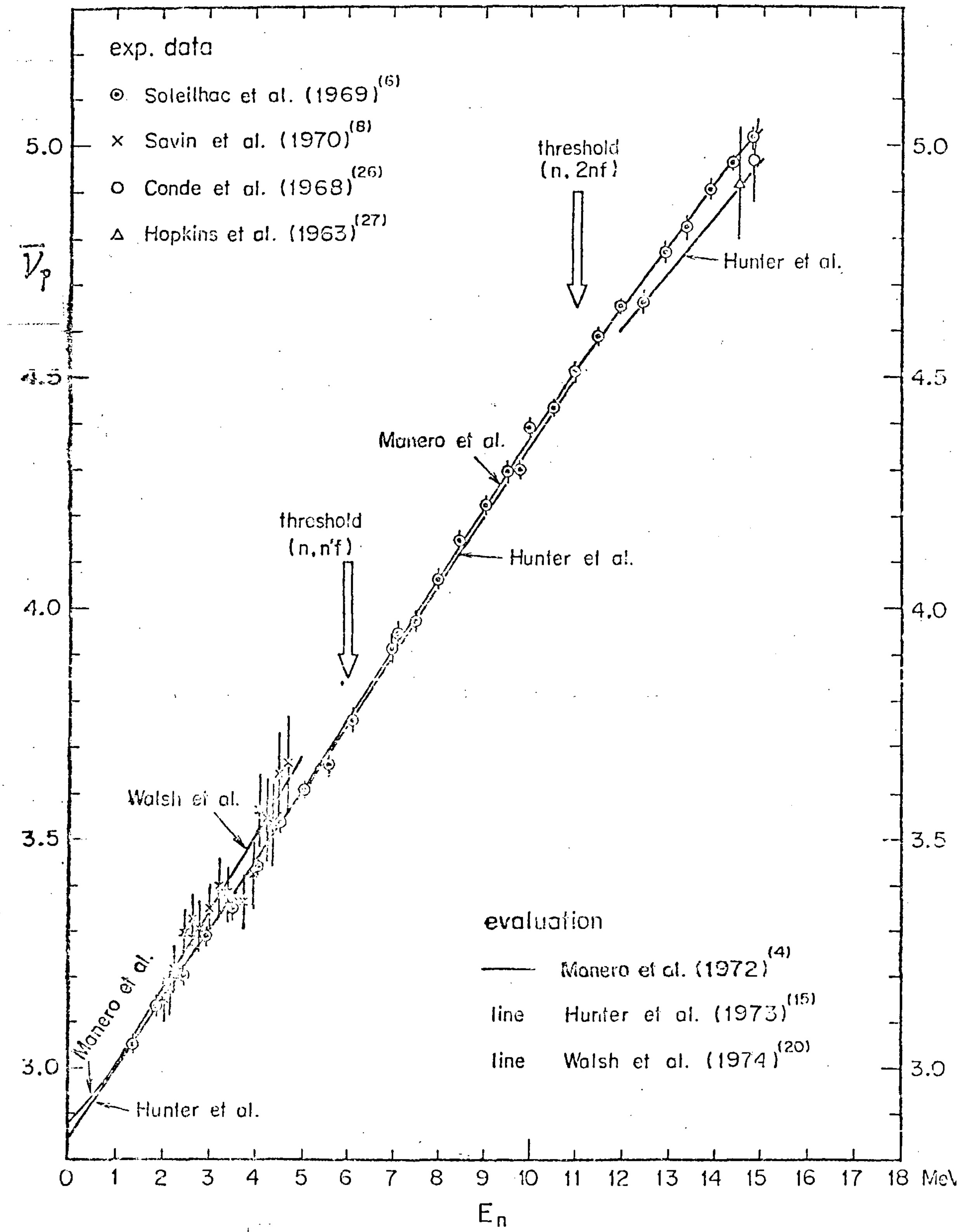

Fig. 4 $\overline{\nu}_p$ of Pu − 239 ($\overline{\nu}_p^{sp}$(Cf−252) = 3.756)

(iv) In WRENDA 75, the data for $\bar{\nu}_p$ of ^{239}Pu are requested as follows:

[Energy Range]	[Accuracy]	[Priority]	
25.3 MV - 10.0 MEV		1	(accuracy 0.5 % from 1 keV to 3 MeV)
- 15.0 MEV	0.5 %	1	
25.3 MV - 2.50 MEV	0.5 %	2	
- 15.0 MEV		1	(accuracy 1 % above 1 keV)
5.00 KEV - 10.0 MEV		1	(accuracy 1 % from 0.1 - 0.8 MeV)

The data measured by Soleilhac et al. (1969)[6] agree with the recommended curve by Manero et al. (1972)[4] almost within their measured accuracy of 0.5 % up to 15 MeV. This apparently fulfils the request of measurement within 1 % accuracy, but discrepancies among the recommended values by Manero et al., Walsh et al., and Hunter et al. in 2.5 - 5 MeV and above 11.5 MeV remain to be solved.

Note added in proof

Work on the evaluation by Prokhorova et al. (1976) [28)]

Discrepancies of the results compared with those of Konshin and Manero are small, and in energy intervals where new data have appeared do not amount to more than 0.5%.

The existence of singularities on the curve for ^{235}U, involving both the broad stepped structure and the fine structure (E_n = 0.2 - 0.5 MeV) is supported. The results of analysis for ^{239}Pu also indicate the presence of the stepped structure in the energy range of 1.2 - 1.5 MeV, though not as pronounced as in the case of ^{235}U.

Work on the evaluation by Boldeman et al. (1977) [29)]

This paper adopted $\overline{\gamma}^{sp}(^{252}Cf)$ = 3.745 as a standard. Corrections of the large liquid scintillator measurements of Boldeman et al. [10)] and Soleihac et al. [6)7)] for the delayed γ rays from fission were made to produce consistent values of the original data more or less. As a result, both measurements do not support the existence of fine structure between 200 and 600 KeV, and the corrected data can be expressed as follows.

$\overline{\gamma}_p(E) = 2.389\ (\pm 0.009) + 0.114E$ 0.1 to 2 MeV

The fine sturcture was not displayed also by the measurements of the mass and kinetic energy distribution of the fission fragments of ^{235}U in an energy range from 450 to 610 KeV by Seregina et al. [30)] An examination of the similar experiments was reported by Boldeman et al. [31)] The results support the case for the absence of fine structure and a linear dependence of $\overline{\gamma}_p(E)$ with any deviation being less than 0.5%.

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