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# ENDF-300
# STANDARD REFERENCE AND OTHER IMPORTANT NUCLEAR DATA BY THE CROSS SECTION EVALUATION WORKING GROUP

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# INTRODUCTION

This report is a current review of the status of standard reference and other important nuclear data pointing out data discrepancies, recommending new measurements and comparing the current version of ENDF/B with data. The loose-leaf format of the report should help future revisions of the different articles and their updating as required. It is hoped that this will be a continuing effort and supplement similar reviews of data status and discrepancies. Articles on some of the topics could not be included in this issue of the report; their titles are given in the Table of Contents. However, there are plans to make them available at a future date.

Individual contributions to this report are by the members of the Normalization and Standards Subcommittee of the Cross Section Evaluation Working Group (CSEWG). Bo Leonard has been the Chairman of this Subcommittee since October 1969. Under his able leadership, this Subcommittee has played an essential role in the working of CSWEG and the evaluated data it has produced over the last thirteen years. He was also instrumental in the planning of this report and its completion. Many thanks are also due to the other members of the Subcommittee, especially Leona Stewart, who reviewed the different articles and suggested various improvements. This report was assembled by Mulki Bhat of the National Nuclear Data Center and any errors or oversight may be communicated to him.

S. Pearlstein
Chairman, CSWEG

# HYDROGEN SCATTERING CROSS SECTION, $^{1}H(n,n)^{1}H$

by

Leona Stewart and Philip G. Young

June, 1979

## ABSTRACT

The status of the hydrogen scattering cross section is reviewed with particular emphasis on standards applications. The ENDF/B-V evaluation is described in detail and compared with experimental data.

## I. DESCRIPTION

The hydrogen scattering cross section is the only standard which presently satisfies acceptable criteria for standards applications above 100 keV. That is, it has no structure and is known with sufficient accuracy to be used as a reference cross section. This cross section is highly recommended for the range from a few keV to 20 MeV and, when used in conjunction with a 1/v cross section up to a few keV, the energy range for applied programs can be well covered. The total cross section is often referred to as "the standard". This is not the case, since the total cross section can only be used to check the integral of the elastic scattering angular distributions.

The recoil proton is usually the detected particle. If used in a proton-telescope arrangement, some kind of radiator is employed whose thickness limits the recoil-proton range (and therefore the neutron energy to be investigated). Whenever a telescope is used, the angular distribution of the protons becomes the dominant factor in setting the accuracy to be associated with the use of this standard. This is particularly important when the observed solid angle is small.

## II. STATUS

The total cross section for hydrogen is essentially equal to the elastic scattering integral above a few hundred eV. The total cross section is well known, but the angular distributions of the neutrons (and recoil protons) are not well determined experimentally on an absolute scale at any incident neutron energy up to 20 MeV.

The $^1$H evaluation for ENDF/B-V (MAT 1301) is basically the same as Version III and Version IV, except for the changes in interpolation rules and the addition of correlated error data in MF=33. This evaluation is well documented in LA-4574-MS (1971), LA-6518-MS (1976), and LA-7663-MS (1979).

### A. General Description of ENDF/B-V

For an extensive summary of the status of the hydrogen cross section including historic advances, see the report to the INDC by C. A. Uttley.[1] The only comment which requires updating in that report refers to a lower 180° cross section between 23 and 29 MeV reported by Drosg.[2] Actually, Drosg's data were "inferred" rather than "measured" and were later found to be in reasonable agreement with the Hopkins-Breit analysis.

Since the ENDF file has been highly recommended for international use since 1972 and Uttley finds the Hopkins-Breit analysis gives excellent shape agreement with a recent Harwell angular distribution measurement at 27.3 MeV[3] when combined with the Wisconsin results,[4] only the ENDF evaluations are compared in the following sections.

The theoretical analysis of fast-neutron measurements by Hopkins and Breit[5] was used to generate the scattering cross section and angular distributions of the neutrons for the ENDF/B-V file.[6] The code and the Yale phase shifts[7] were obtained from Hopkins[8] in order to obtain the data on a fine-energy grid. Pointwise angular distributions were produced to improve the precision over that obtained from the published Legendre coefficients.* The phase shifts were also used to extend the energy range down below 200 keV as represented in the original paper.[5]

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*For $E_n$ = 30 MeV, the difference in the 180° cross section is ~1% as calculated from the Legendre coefficients[5] compared to that calculated from the phase shifts.

At 100 eV, the elastic cross section calculated from the phase shifts is 20.449 barns, in excellent agreement with the thermal value of 20.442 ± 0.023 barns derived by Davis and Barschall.[9] Therefore, for the present evaluation, the free-atom scattering cross section is assumed to be constant below 100 eV and equal to the value calculated from the Yale phase shifts at 100 eV giving a thermal cross section of 20.449 b.

## B. Total Cross Sections

Total cross-section measurements are compared with the evaluation in Fig. 1 for the energy range from 10 eV to 0.5 MeV. Similarly, Figs. 2 and 3 compare the evaluation with measured data from 0.5 to 20 MeV. The agreement with the earlier experiments shown in Fig. 2 is quite good over the entire energy range. The 1969 data of Schwartz[10] included in Fig. 3, however, lie slightly below the evaluation over most of the energy range even though agreement with the 1972 results of Clement[11] is quite acceptable. The Wisconsin data[12] are compared from 1.5 to 20 MeV with ENDF/B-V in Fig. 4 along with the very precise value[13] at 2.533 ± 0.003 MeV of 2.536 ± 0.0015 barns. Data from KFK and Harwell which are not shown in these figures also tend to support the ENDF curve reasonably well. At the same time, it would be useful to have a few points measured with excellent precision as further checks on the phase-shift analysis.

At this time, no attempt has been made to estimate the effect of errors on the energy scale in ENDF/B. It is clear, however, that a small energy shift would produce a large change in the cross section, especially at low energies. For example, a 50-keV shift in energy near 1 MeV would produce a change in the standard cross section of approximately 2½%. Therefore, precise determination of the incident neutron energy and the energy spread could be very important in employing hydrogen as a cross-section standard, depending upon the experimental technique.

## C. Angular Distributions

Unfortunately, few absolute values of the angular dependence of the neutrons (or recoil protons) exist and even the relative measurements are often restricted to less than half of the angular range. The experiment of Oda[14] at 3.1 MeV is not atypical of the earlier distributions which, as shown in Fig. 5, does not agree with the phase-shift predictions. Near 14 MeV, the T(d,n) neutron source has been employed in many experiments to determine the angular distributions. A composite of these measurements is compared with ENDF/B-V in Fig. 6 Note that most of the experiments are in reasonable agreement on a relative scale, but 10% discrepancies frequently appear among the data sets. The measurements of Cambou[15] average more than 5% lower than the predicted curve and differences of 5% or more are occasionally apparent among the data of a single set. Figure 7 shows the measurements of Galonsky[16] at 17.9 MeV compared with the evaluation. Again, the agreement on an absolute basis is quite poor.

Elastic scattering angular distributions at 0.1, 5, 10, 20, and 30 MeV are provided in Ref. 3 as Legendre expansion coefficients. Using the Hopkins-Breit phase-shift program and the Yale phase shifts, additional and intermediate energy points were calculated for the present evaluation.[6] As shown in Figs. 4 and 5, the angular distributions are neither isotropic below 10 MeV nor symmetric about 90° above 10 MeV as assumed in earlier evaluations. In this evaluation, the angular distribution at 100 keV is assumed to be isotropic since the calculated 180°/0° ratio is very nearly unity, that is, 1.0011. At 500 keV, this ratio approaches 1.005. Therefore, the pointwise normalized probabilities as a function of the center-of-mass scattering angle are provided at the following energies: $10^{-5}$ eV (isotropic), 100 keV (isotropic), 500 keV, and at 1-MeV intervals from 1 to 20 MeV.

Certainly the Hopkins-Breit phase shifts reproduce reasonably well the measured angular distributions near 14 MeV. It is important, however, that experiments be made at two or three energies which would, hopefully, further corroborate this analysis. Near 14 MeV, the energy-dependent total cross section is presently assumed to be known to ~1% and the angular distribution to 2-3%. At lower energies where the angular distributions approach isotropy, the error estimate on the angular distribution is less than 1%.

## III. CONCLUSIONS AND RECOMMENDATIONS

### A. Measurements

1. Precision total cross section measurements are needed at a few energies. (Experiments are currently under way by W. P. Poenitz, ANL).
2. Angular distributions on an absolute basis are needed at a few energies. This experiment should be performed near 14 MeV using T(D,n) or D(t,n) neutrons where the associated alpha particle will provide the absolute flux monitor. Other energy points would also be useful.

## B. Evaluations

Several years have passed since the Hopkins-Breit phase-shift analysis was performed. Recent phase-shift analyses carried out by Bohannon et al.[57] in 1976 and by Arndt et al.[58] in 1977 agree reasonably well with each other and with Hopkins-Breit and the LLL constrained set. These analyses emphasize the need for precise angular distribution measurements which cover a wide angular range in order to improve the precision obtainable for the value of $\delta(^1P_1)$.

It is very doubtful whether a new phase-shift analysis using the existing relative angular distribution measurements would provide data with better accuracy than already quoted for the Yale phase-shift analysis. It may be worthwhile, however, to perform a simultaneous charge-independent analysis of the n-p and p-p systems since p-p experimental data cover a wide energy range and the charged-particle measurements have very small associated errors.

## C. Standard's Use

It should be pointed out that errors involved in using hydrogen as a standard depend upon the experimental techniques employed and therefore may be significantly larger than the errors placed on the standard cross section itself. The elastic angular distribution measurements of neutrons scattered by hydrogen, which are available today, seem to indicate that $\sigma(\theta)$ is difficult to measure with the precision ascribed to the reference standard. If this is the case, then the magnitude of the errors in the $\sigma(\theta)$ measurements might be indicative of error assignments which should be made on hydrogen flux monitors. That is, it is difficult to assume that hydrogen scattering can be implemented as a standard with much higher precision than it can be measured. Even though better agreement with many past measurements can be reached by renormalizing the absolute scales, such action may not always be warranted.

## ACKNOWLEDGMENTS

We appreciate the thorough review of this report by T. W. Burrows and his timely additions to the reference list. In addition, he provided Fig. 4 which indicates excellent agreement with the 1971 Wisconsin results.

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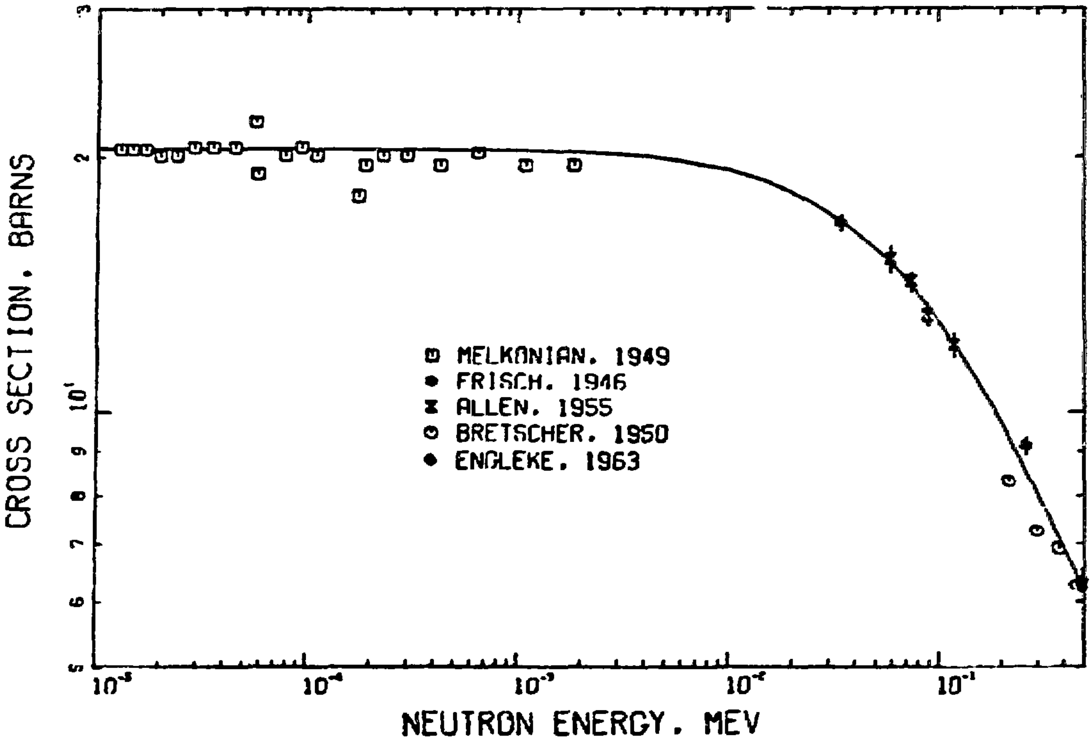

Fig. 1.
Total cross section for hydrogen from $10^{-5}$ MeV to 0.5 MeV. The ENDF/B-V evaluation is compared to the measurements of Refs. 18–22.

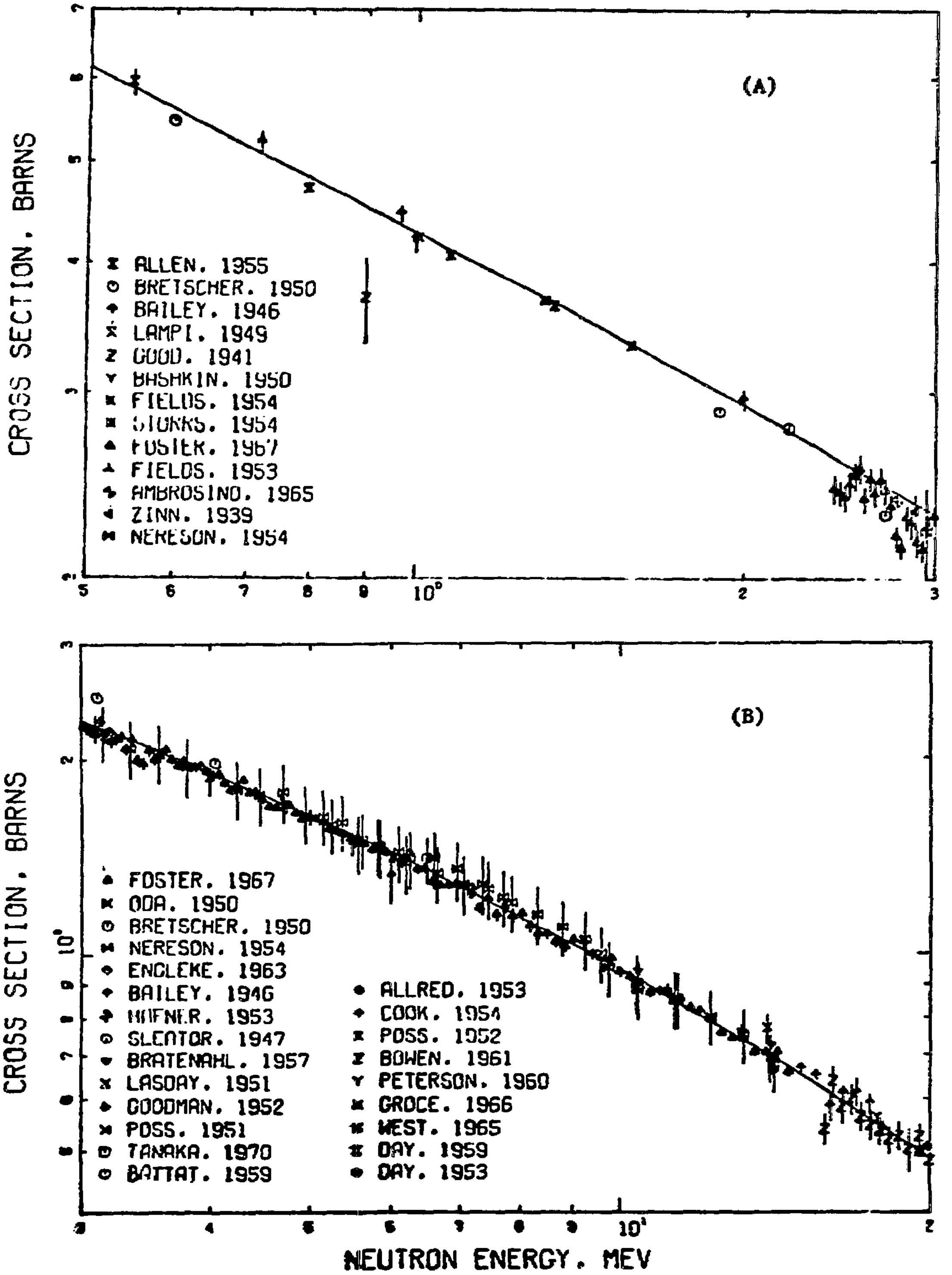

Fig. 2.
Total cross section for hydrogen from 500 keV to 20 MeV. The ENDF/B-V evaluation is compared to measurements reported in Refs. 14, 20-51.

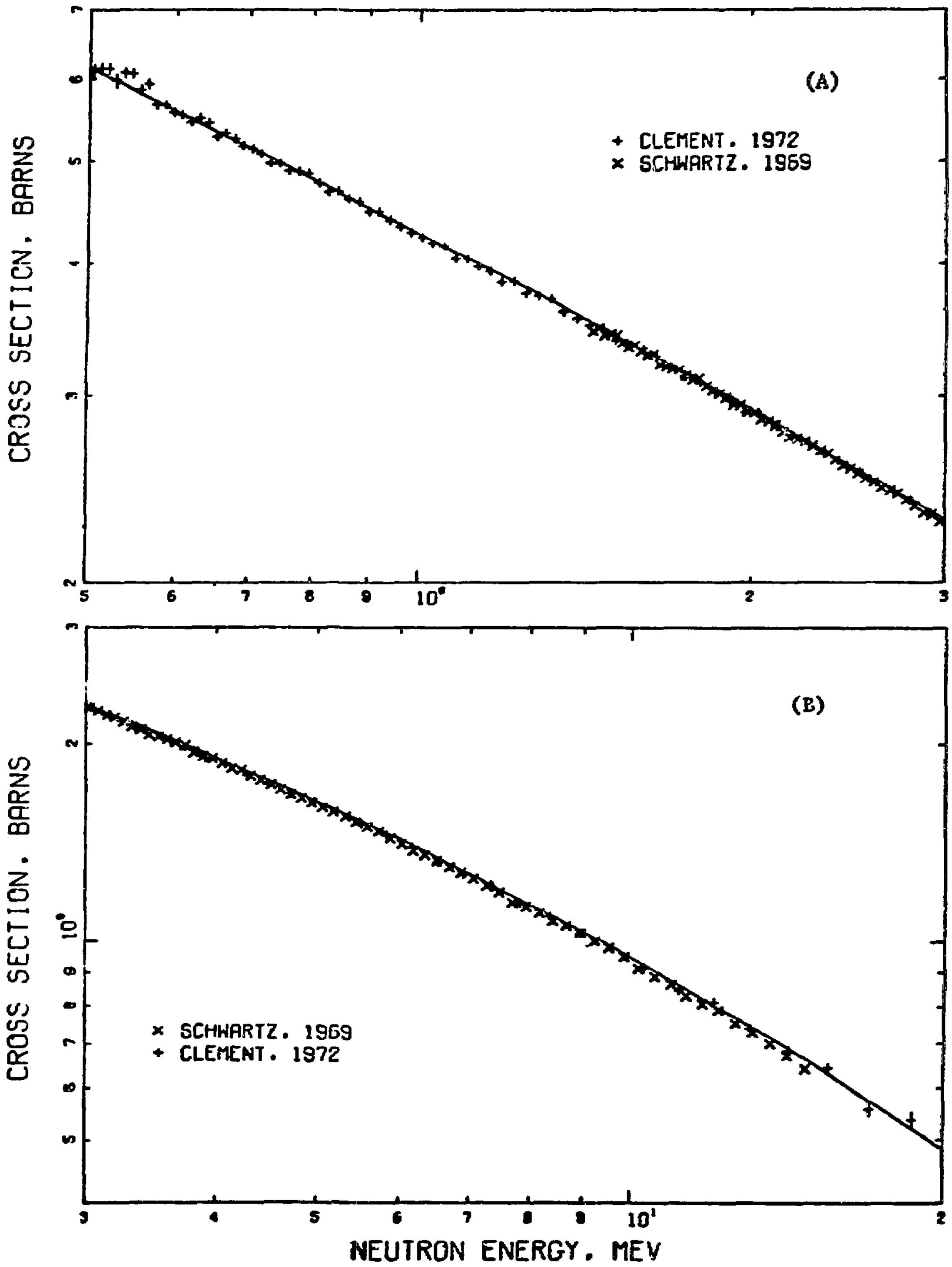

Fig. 3.
Total cross section for hydrogen from 500 keV to 20 MeV. The ENDF/B-V evaluation is compared to measurements reported in Refs. 10 and 11.

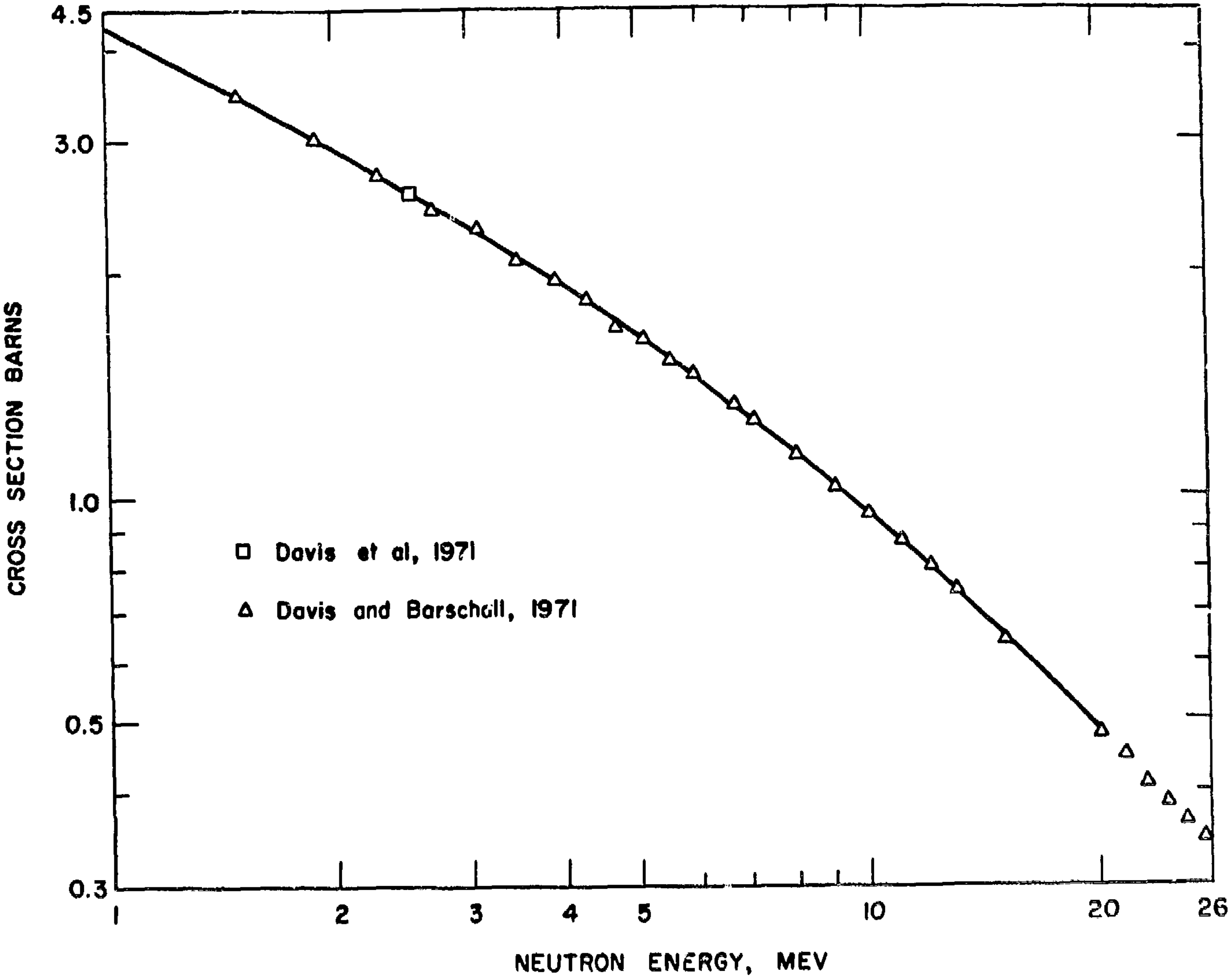

Fig. 4.

Total cross section for hydrogen from 1 to 26 MeV. The ENDF/B-V evaluation is compared to the Wisconsin measurements of Refs. 12 and 13. (Note that the symbols are larger than the experimental errors on these very precise measurements).

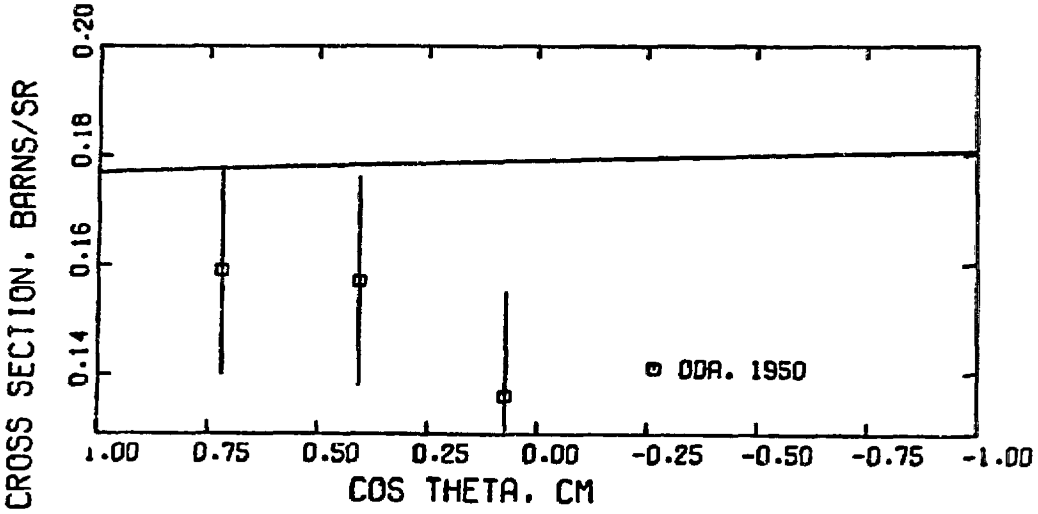

Fig. 5.
Angular distribution of the neutrons elastically scattered from hydrogen at 3.1 MeV. ENDF/B-V is compared with the experimental values of Oda.[14]

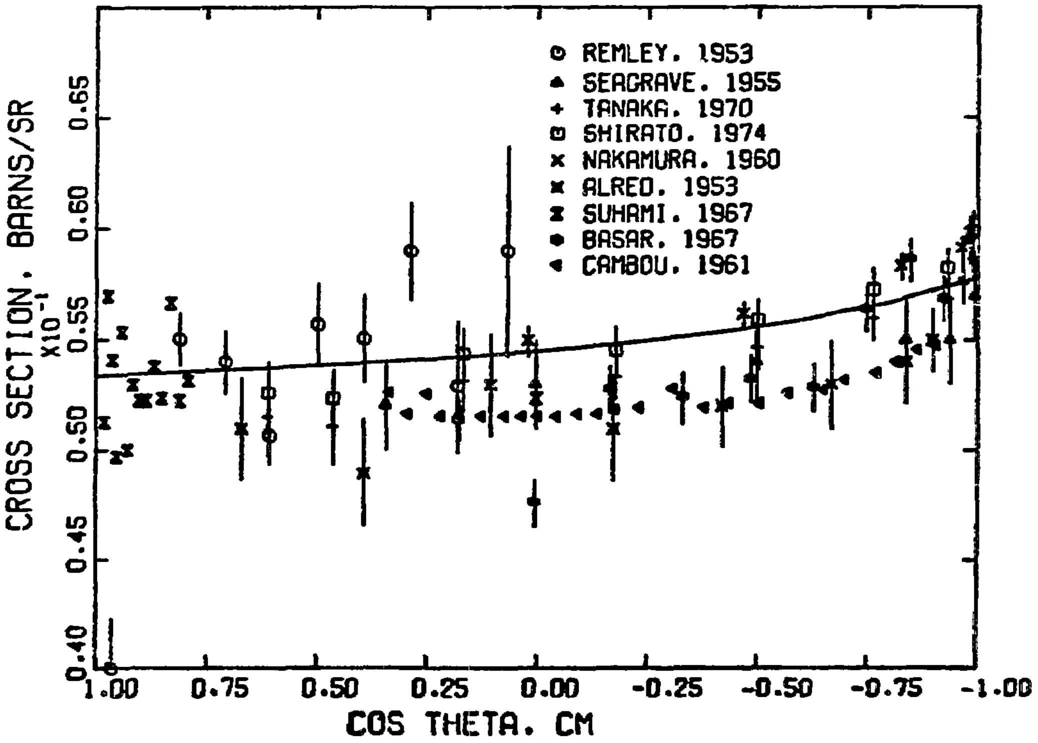

Fig. 6.
Angular distribution of the neutrons elastically scattered from hydrogen at energies near 14 MeV. The experimental data shown were reported in Refs. 15, 40, 42 and 51-56.

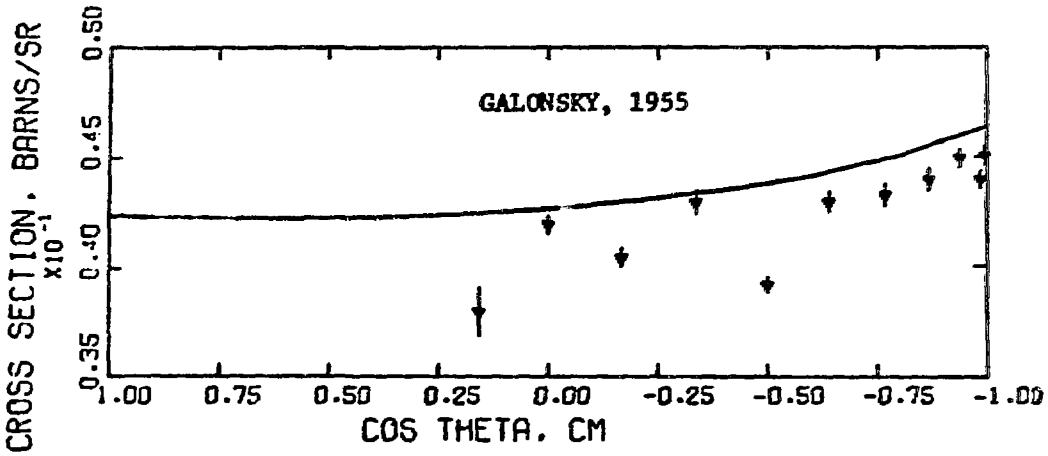

Fig. 7.
Angular distribution of the neutrons elastically scattered from hydrogen at energies near 17.8 MeV. The experimental data shown were reported in Ref. 16.

# The $^3$He(n,p)T Cross Section

A.D. Carlson

October, 1979

## Description

This standard has been used for cross-section measurements, determinations of neutron flux and for investigations of neutron spectra emitted by nuclei. The cross section for this reaction is very large and has a smoother energy dependence than most of the other standard cross sections. Its gradual change in cross section with neutron energy is particularly noteworthy from $\frac{1}{2}$ MeV to 2 MeV where both the $^6$Li(n,α)T and $^{10}$B(n,α)$^7$Li cross sections are changing rapidly with neutron energy. Also molecular effects (1) which may be present when using some of the standard cross sections are not present with the $^3$He(n,p)T reaction. This cross section has been proposed as a standard for neutron energies below 3 MeV. The measurements of cross sections relative to this standard have been largely limited to low neutron energies due to the uncertainty in the cross section and problems associated with the implementation of this reaction. Measurements of neutron flux (and spectra) can be obtained with monoenergetic neutrons or with white sources when the time-of-flight technique can be used. It is also possible to utilize unfolding techniques with high resolution counters which have well-defined response functions.

## Status

The measurements of the $^3$He(n,p) cross section from 100 eV to 10 MeV are shown in Fig. 1. There have been no measurements reported on this standard since 1970. The cross section data, mostly obtained from T(p,n)$^3$He measurements by reciprocity, are listed by Liskien & Paulsen (2). Earlier measurements are described and compared in the evaluation for ENDF/B performed by L. Stewart (3). Although this evaluation was performed in 1968, it has been carried over intact from version III to version IV to version V. Comparisons are made with experimental data for neutron energies up to 1 MeV.

The cross section can certainly be measured more accurately with present day facilities and techniques.

## Comments and Recommendations

The $^3$He(n,p)T cross section has been implemented with gas proportional counters (4,5,6), ionization chambers (7,8,9), solid state detectors (10), gas scintillators (11), and liquid scintillators (12). The proportional counters and ionization chambers have rather poor timing for time-of-flight measurements and have low efficiency for high-energy neutrons. These counters and those using solid state detectors, however, produce pulse height distributions which can be conveniently unfolded. Gas scintillator detectors have been made which provide good timing and efficiency but suffer from poor pulse height resolution. More work should be done to improve the performance of these counters. It is interesting, however, that the most recent cross section measurements (13,14,15), using the $^3$He(n,p)T reaction for neutron detection have utilized gas scintillators. A $^3$He liquid scintillator has recently been developed by Staa (12) which has high efficiency and good timing and pulse height resolution for MeV neutrons. This type of detector may have many useful applications for both time-of-flight experiments and those employing unfolding if the difficulties associated with its fabrication and use are acceptable.

The uncertainties in the $^3$He(n,p)T cross section are unfortunately large, particularly above 100 keV where they are estimated to be 7-10%. With the unfolding techniques that are now becoming available this may be a significant portion of the uncertainty in measurements such as energy spectra of delayed neutrons.

In order not to inhibit any technological developments which may provide an improved implementation of this cross section, it is recommended that the $^3$He(n,p)T cross section be retained as a standard but efforts to improve the cross section should be consistent with the needs.

The NBS is measuring the ratio of the $^3$He(n,p)T cross section to the $^{10}$B (n,$\alpha$)$^7$Li cross section at the NBS Filtered Beam Facility. This will provide an improved $^3$He cross section which can be conveniently used at filtered beam facilities for neutron flux determination.

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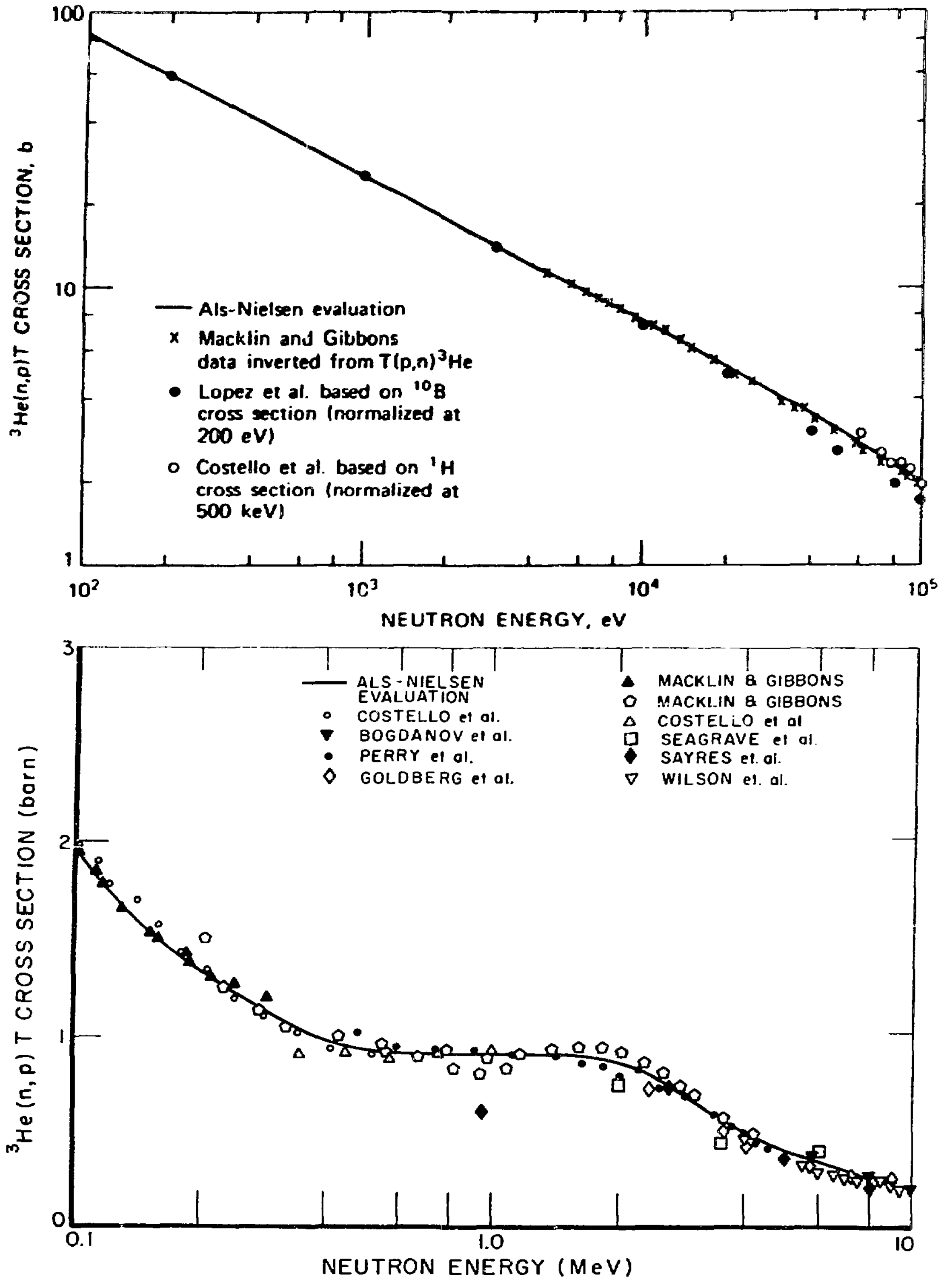

FIG. 1. Measurements of the $^3$He(n,p)T cross section. The references to all the experimental work (except Goldberg (16)) are contained in Ref. 4.

# $^{6}$Li(n,t)$^{4}$He

Gerald M. Hale

July 12, 1979

## DESCRIPTION

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. The recommended energy range for use as a standard is thermal -- 100 keV, a region in which the cross section begins to deviate substantially from 1/v behavior. However, applications in which the cross section is used as a standard at energies over the 240 keV resonance and up to a few MeV are not uncommon. The cross section is also of interest at energies up to several MeV because lithium is envisaged as a tritium-breeding medium in most fusion designs. With the standards application mainly in mind, we will limit the discussion of this review to energies below 1 MeV.

## STATUS

Measurements of the neutron cross sections for $^{6}$Li made before 1975 were inconsistent with unitary constraints relating them, particularly near the peak of the 240-keV resonance. That situation has improved significantly in the past few years, in that recent measurements of the (n,t), total, and elastic cross sections agree to the order of a few percent with each other and with calculations[1-3] that impose unitary consistency.

The most comprehensive of these calculations is an R-matrix analysis[1] from which low-energy neutron cross sections for $^{6}$Li (including the standard (n,t) cross section) were obtained for Version V of ENDF/B. Included in this analysis were recent LASL measurements of t-α differential cross sections and analyzing powers[4], as well as the new measurements of the total cross section of Harvey[5] (ORNL) and of relative (n,t) cross sections of Lamaze[6] (NBS). The R-matrix analysis gives a peak (n,t) cross section of 3.31 b at 240 keV and a peak total of 11.26 b at 245 keV. The 5-keV difference between the peak cross section of the total and (n,t) as predicted in the analysis agrees closely with the measurements of Harvey[5] and Lamaze[6], without shifting either energy scale. The cross sections predicted at the peak, however, are ∿2 and 5% higher, respectively, than these measurements indicate. At energies below 200 keV, the agreement of the calculated $\sigma_{n,t}$ cross section with Lamaze's relative data* is generally better than 2%, and the agreement of the calculated $\sigma_T$ with Harvey's data is generally better than 1%, except for a region around 150 keV where the difference is ∿5%. The predicted thermal value of the (n,t) cross section is in excellent agreement with the recommended value of 936 b.

Knitter[3] has reported measurements of $\sigma_T$ between 80 keV and 3 MeV as well as an extension of his earlier $^6$Li(n,n) angular distribution measurements down to 100 keV. Recent work by Smith[7] at ANL supplements the Geel total cross-section data and extends the scattering measurements to 4 MeV. Fitted values[3,7] of the total, elastic, and (n,t) cross sections based on these measurements agree very well with the Version V results. Knitter's (fitted) resolution-corrected value for the peak neutron total cross section is 11.27 ± 0.12 b at 247 ± 3 keV, while that obtained from the new ANL measurements is 11.2 ± 0.2 b at 244.5 ± 1.0 keV.

Among the new measurements of the $^6$Li(n,t) integrated cross section reported since the Version V standards analysis was completed are those of Gayther[8] at Harwell and of Renner et al.[9] at ORNL. The Gayther[8] data, measured relative to $^{235}$U(n,f) at energies between 3 and 800 keV agree very well with the Version V $^6$Li(n,t) results when converted with Sowerby's $^{235}$U(u,f) evaluations. This agreement may be fortuitous, since the Sowerby evaluation does not represent current thinking about the "best" $^{235}$U(n,f) cross sections in this energy range. The Renner measurements,[9] taken at "iron windows" between 80 and 470 keV, are also consistent with the Version V results, except possibly for a small normalization difference, as determined from a later fit in which the Lamaze data were replaced by the Renner[9] data.

The measurements of Brown et al.[10] at LASL of $\sigma_{n,t}(0^o)$ and $\sigma_{n,t}$ $(180^o)$ from the T(α, $^6$Li)n inverse reaction confirm a resonance energy of 240 keV and generally agree well with the Version V predictions. Measurements made with thin targets of the asymmetry of the $^6$Li(n,t) angular distribution at 2 and 24 keV reported recently by Stelts et al.[11] agree well with predictions of the Version V analysis. Raman et al.[12] have also studied the asymmetry of the $^6$Li(n,t) angular distributions from 0.5 eV to 25 keV in a thick-target geometry.

Macklin[13] has recently recalibrated his $^6$Li flux monitor in the 0.07-3 MeV range by comparing with the $^{235}$U(n,f) cross section. The monitor response, when

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*The NBS relative data were converted using the Gammel representation for the (n,p) cross section which as Poenitz has pointed out differs from the Hopkins-Breit representation by ∿1% in the low energy region.

converted with the Version V $^{235}$U(n,f) cross section, is in substantially better agreement with the Version V $^{6}$Li(n,t) cross sections below 500 keV than that obtained previously. There remains, however, an apparent difference in the width of the 240-keV resonance.

## CONCLUSIONS AND RECOMMENDATIONS

A long-standing restriction on the usefulness of the $^{6}$Li(n,t) cross section at all but the lowest energies has been the lack of reliably determined neutron cross sections for $^{6}$Li over the 240-keV resonance. The recent measurements and Version V ENDF evaluation represent a considerable improvement in that situation, achieving generlly good intenal agreement and, perhaps more importantly, unitary consistency among the cross sections over the resonance. Therefore, an appropriate goal of the next update of the $^{6}$Li ENDF evaluation would be to produce a $^{6}$Li(n,t) cross section that can be recommended as a standard up to much higher energies than the present 100 keV limit.

While the data that have appeared since the evaluation was completed tend to affirm that the present version is close to that goal, they also point out discrepancies that should be resolved. Some of them are as follows.

1. Differences over the resonance between the $^{6}$Li(n,t) measurements of Renner et al.[9] which appear to be supported by Macklin's recent flux determination[13], and those of Lamaze et al.[6] at NBS.
2. Differences over the resonance, apart from energy shifts, between measurements of the total cross section by Knitter et al.[3] which appear to be supported by Smith et al.[7] and those of Harvey and Hill[5].

The Renner measurements[9] must be considered in conjunction with Harvey's measurement[5] of $\sigma_T$, since the target thickness in the former experiment was determined by the latter.

Another area of experimental concern, if the energy range of the standard is to be extended, is the region 0.8-3 MeV where the few existing measurements disagree severely. This region contains the next identifiable resonance feature in the $^{6}$Li(n,t) cross section above the 240 keV resonance — a "shoulder" at $\sim$2 MeV due to the $3/2^-$ state[1]. Experiments are in progress at Uppsala[14] to measure $^{6}$Li(n,$\alpha$) and T($\alpha$,$^{6}$Li) angular distributions in the vicinity of this anomaly.

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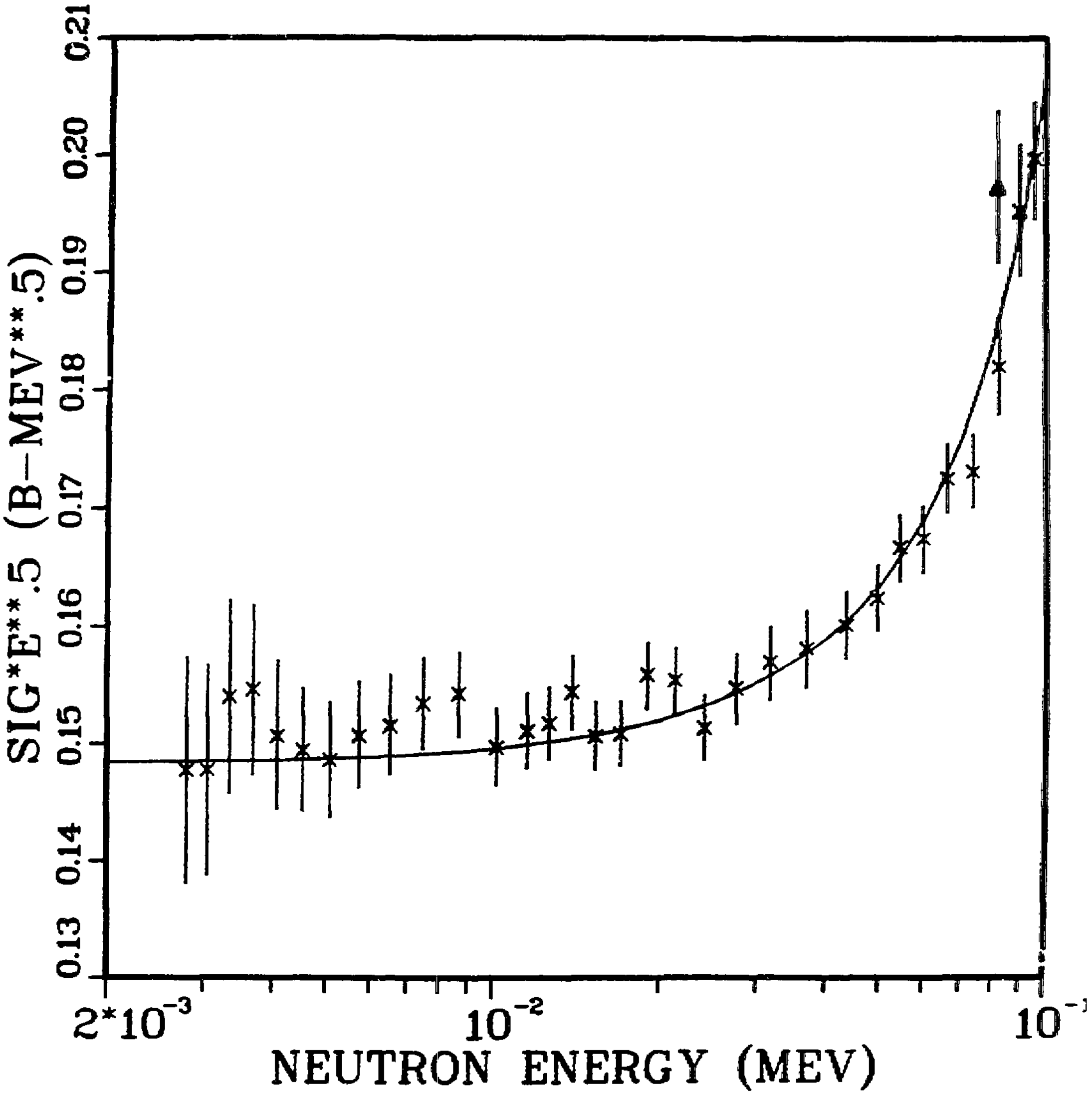

Fig. 1.

ENDF/B-V $^{6}$Li(n,t) cross section (solid curve) compared with the measurements of Lamaze et al.[6] (x) and of Renner et al.[9] (Δ) at energies below 100 keV. The cross sections are scaled by $\sqrt{E}$ to remove the 1/v dependence at low energies.

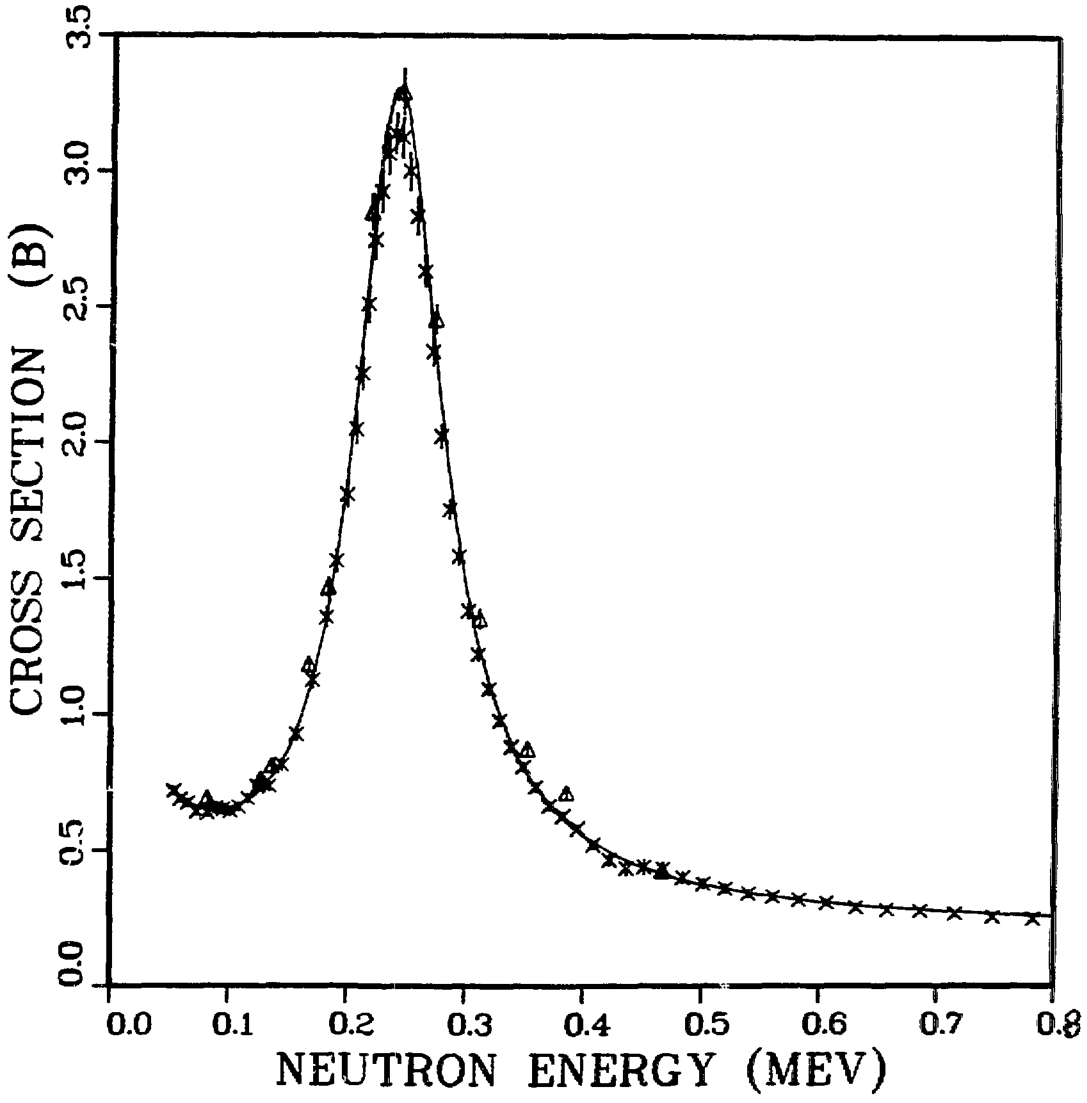

Fig. 2.

ENDF/B-V $^{6}$Li(n,t) cross section (solid curve) compared with the measurements of Lamaze et al.[6] (x) and of Renner et al.[9] (Δ) at energies between 50 and 800 keV.

# $^{10}B(n,\alpha_0)^7Li$ and $^{10}B(n,\alpha_1)^7Li^*$

Gerald M. Hale

July 12, 1979

## DESCRIPTION

The cross sections for these reactions are particularly attractive as standards since they are large and relatively structureless over a broad energy range (0-500 keV). They are presently recommended for standards use at energies up to 100 keV. Measurements have been made for the separate $(n,\alpha_0)$ and $(n,\alpha_1)$ cross sections as well as for the total $(n,\alpha) = (n,\alpha_0) + (n,\alpha_1)$. Energy-dependent observations of the 480-keV gamma decay of the $^7Li^{*1}$ and branching-ratio measurements of the $\alpha_0/\alpha_1$ have also been made in the low-energy region. Finally, experiments on the ratio of the $^6Li/^{10}B$ total (n,α) have been carried out at low energies. It is unfortunate that most of the latter measurements have been restricted to energies in which both the $^6Li$ and $^{10}B$ cross sections are essentially 1/v.

## STATUS

Most of the evaluation work on the $^{10}B(n,\alpha_0)$ and $^{10}B(n,\alpha_1)$ cross sections has been limited to considering data for each reaction separately. The most recent of these is the evaluation of Liskien and Wattecamps[1] for $^{10}B(n,\alpha_1)$ between 0.1 and 2 MeV. The evaluations used for Version IV[2] and V of ENDF/B are based on comprehensive extensions[3] of Lane's[4] R-matrix work on the $^{11}B$ system. These extended analyses consider simultaneously data from all the neutron reactions on $^{10}B$ as well as measurements for the $\alpha$-$^7Li$ reactions.

The R-matrix analysis upon which the ENDF/B Version V standard $^{10}B(n,\alpha)$ cross sections are based is similar in many respects to that used for Version IV.[2] Three additional measurements of low-energy neutron cross sections for $^{10}B$ became available for input into the Version V analysis:

1. Relative measurements[5] of the $^{10}B(n,\alpha_1)^7Li^* \rightarrow \gamma$ decay at NBS† using both a NaI and a Ge(li) detector to record the 478-keV gamma. Measurements extended from approximately 5 to 600 keV.
2. $^{10}B(n,\alpha)^7Li$ differential cross-section measurements[6] between 0.2 and 1.25 MeV.
3. Neutron total cross section measurements[7] at energies between 90 and 420 keV.

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†These shape measurements relative to hydrogen were converted using the Gammel representation of the n-p cross section which, as Poenitz has pointed out, differs from the Hopkins-Breit representation by ~1% in the low-energy region.

The main effect of adding these data was to lower the $^{10}B(n,\alpha_1)$ cross section relative to Version IV between 200 and 1000 keV. Excellent agreement with the $^{10}B(n,\alpha_0)$ measurements of Macklin[8] and Davis[9] was maintained. We note that the $(n,\alpha_0)$ measurements of Sealock and Overley[6] were not used in the analysis due to disagreement with all previous results. They have since checked their $(n,\alpha_0)$ data by measuring $^7Li(\alpha,n_0)$ angular distributions,[10] and find that the major shape differences[6] with the integrated cross-section measurements of Macklin and Gibbons[8] have vanished but that differences in normalization of the order 10-18% remain.

Since the Version V standard evaluation was completed, new measurements of the $^{10}B$ total cross section,[11] of the $^{10}B(n,\alpha_0)$ and $^{10}B(n,\alpha_1)$ angular distributions at low energies,[12] and of the $^{10}B(n,\alpha_1)$ integrated cross section[13] have become available. The agreement of the Version V results with the low-energy angular distributions of Ref. 12 [in particular the enhanced anisotropy of the $(n,\alpha_0)$ reaction with respect to the $(n,\alpha_1)$ reaction] is quite satisfactory, considering that very little experimental information concerning these effects had been included in the analysis. The branching ratios predicted by the Version V analysis are in relatively good agreement with this experiment[12] at low energies and compare very well with a value measured at NBS[14] at 790 keV [measured $\frac{\sigma(n,\alpha_1)}{\sigma(n,\alpha)} = 0.66 \pm 0.03$; calculated $\frac{\sigma(n,\alpha_1)}{\sigma(n,\alpha)} = 0.6647$]. The new Geel measurements[13] are in good agreement with the Version V results at energies below 700 keV.

## CONCLUSIONS AND RECOMMENDATIONS

The Version V ENDF/B results appear to represent well the experimental data for the $(n,\alpha_0)$ and $(n,\alpha_1)$ cross sections that were available at the time of the evaluation, and that have since become available, at energies up to $\sim$700 keV. Above that energy, the data of Viesti and Liskien[13] and those of Auchampaugh et al.[11] indicate that changes in the evaluation are required.

It is very likely that additional structure is superimposed on the broad features already identified in the $(n,\alpha)$ cross sections at energies below 1 MeV, since at least three other resonances can be seen in the $\alpha$-$^7Li$ reactions in this energy range. While the affects of these additional levels are probably masked by statistical (or systematic) fluctuations in most of the current neutron measurements, they may be important for determining the (n,$\alpha$) cross sections to standards accuracy using R-matrix methods. For instance, the fact that the calculated Version V (n,$\alpha_1$) cross section falls below the measurements of Viesti and Liskien[13] at energies above 700 keV may very well be due to the neglect of a level barely visible in their data at $E_n$ = 1.3 MeV.

New measurements of $\alpha$-$^7$Li (especially inelastic) angular distributions in the range $E_\alpha$ = 3-6 MeV could be very helpful in identifying the unknown levels in this important region. In addition, absolute measurements having 1-2% accuracy of the $^{10}$B(n,$\alpha_0$) and $^{10}$B(n,$\alpha_1$) cross sections in the few-keV-1 MeV range would be very desirable for resolving remaining questions about the magnitudes and shapes of the broad structure in the cross sections.

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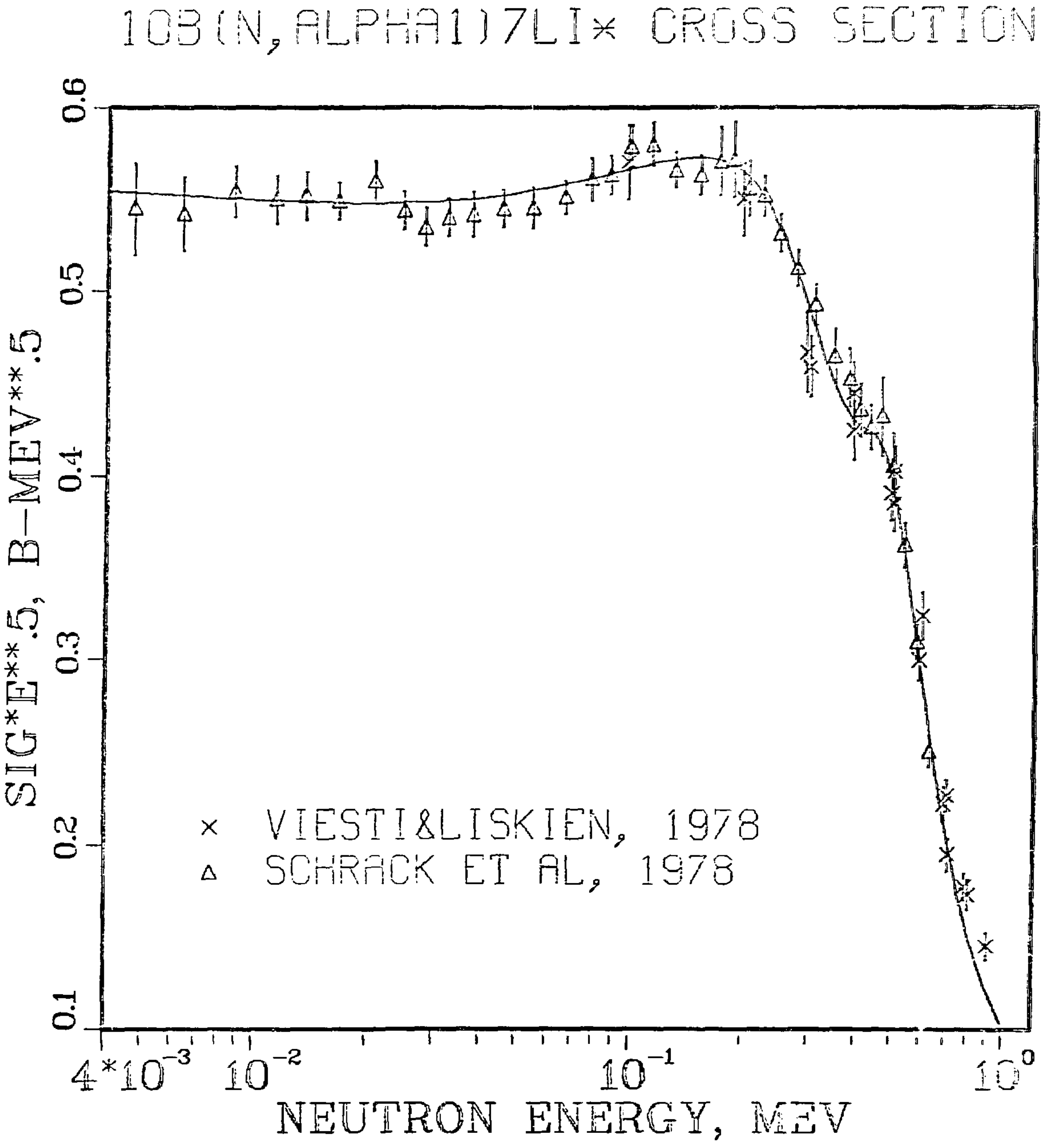
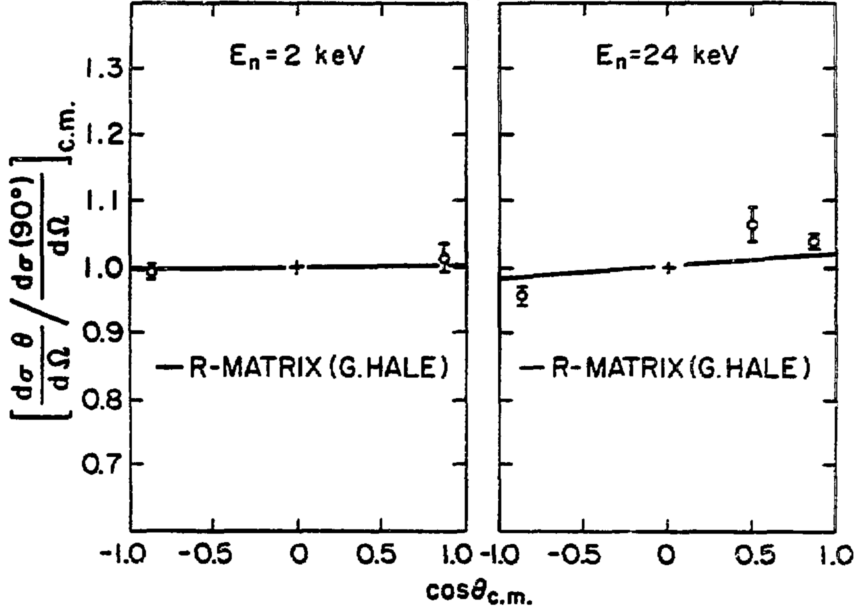


**Fig. 1.**

ENDF/B-V $^{10}B(n,\alpha_1)$ cross section (solid curve) compared with recent measurements by Viesti and Liskien[13] (x) and by Schrack et al.[5] (Δ). The cross sections are scaled by $\sqrt{E}$ to remove the 1/v dependence at low energies.

CENTER-OF-MASS ANGULAR DISTRIBUTION FOR $^{10}B(n,\alpha_1)^7Li^*$



CENTER-OF-MASS ANGULAR DISTRIBUTION FOR $^{10}B(n,\alpha_0)^7Li$

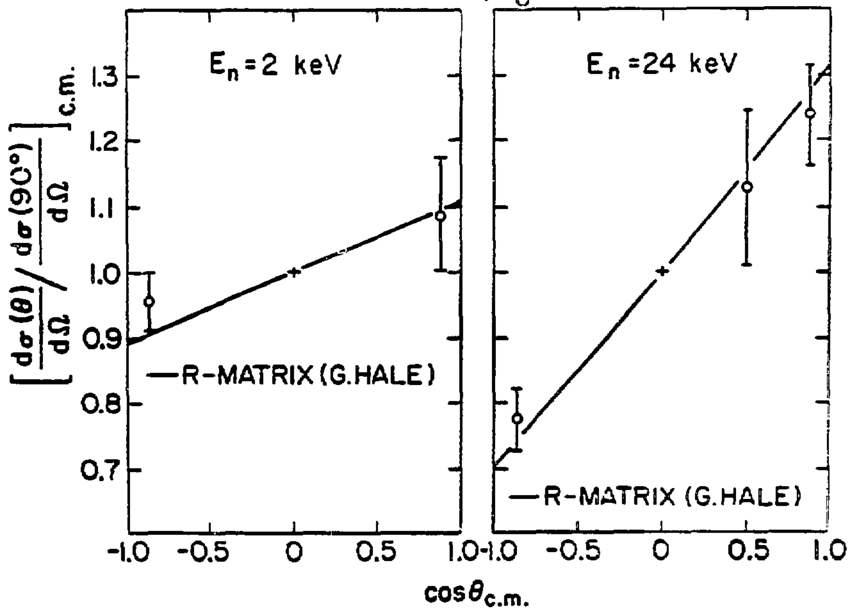


Fig. 2.
Relative angular distributions for the $^{10}B(n,\alpha_1)^7Li^*$ (top) and $^{10}B(n,\alpha_0)^7Li$ (bottom) reactions at 2 and 24 keV. The solid curves are predictions of the ENDF/B-V R-matrix analysis, and the experimental points are those of Stelts et al.[12]

# The Fast Neutron Cross Section of $^{12}C$

by

W.P. Poenitz and A.B. Smith

June 1, 1979

## I. DESCRIPTION

The elastic-scattering cross section of $^{12}C$ is essentially equivalent to the total cross section at energies below the first inelastic threshold of ~4.8 MeV. Capture contributes less than 0.07% at all energies below 20 MeV. The cross section is a smooth function of energy below 2 MeV and resonances above 2 MeV, notably at 2.078 MeV, are suitable energy-scale references. High-purity samples of natural carbon are easily available. $^{13}C$ occurs with 1.11% abundance and its resonances at 0.15, 1.75 MeV and at higher energies must be taken into account. The heavier target mass is a major advantage in some experimental use of this cross section due to the reduced energy loss compared with the H(n,n) standard. Multiple scattering corrections are greatly simplified.

## II. STATUS

A rather surprising diversity exists between all the available total cross section data (see for example BNL 325). However, representative data sets obtained in more recent measurements agree rather well (usually within ~±1%) or differences can be well understood by differences in the resolutions of the experiments. A check at 1 MeV shows data by Perey(1), Schwartz(2), Cabe(3), Uttley(4), Yergin(5), Stoler(6), Cierjacks(7), Smith(8), and Whalen(9) to usually agree to within ±0.5%. The thermal cross section value appears to be well established (better than 0.5%). Somewhat larger differences can be found at higher energies, specifically around 3.5 MeV (~1-2%). A value was reported by Block et al.(10) at 24 keV with small uncertainty limits.

More recent measurements of the differential elastic-scattering cross sections were reported for higher energies by Galati(11), Velkley(12), Haouat(13), and Glasgow(14). Measurements in the range of interest for standard purpose were carried out in great detail by Smith et al.(8).

Evaluations of the carbon total and scattering cross sections usually include an R-function analysis. More recent detailed evaluations are by Lachkar(15), Fu and Perey(16) and Smith et al.(8). The results are very consistant though the R-function parameters may be considerably different. Lachkar(15) gives an expression $\sigma = 4.75 - 3.251 \cdot E + 1.316 \cdot E^2 - 0.277 \cdot E^3$ for energies below 2 MeV which agrees rather well with the evaluation by Fu and Perey(16) (~0.1%) below 500 keV but differs from Ref. 16 by up to 0.8% at higher energies. The evaluation of Fu and Perey(16) is the present ENDF/B-V file. Fu and Perey have also carried out a detailed analysis of the associated errors. A comparison of the evaluation of the total cross section by Fu and Perey (ENDF/B-V) and the most recent measurement at ANL(17) is shown in Fig. 1. This newest experiment supports ENDF/B-V usually within ~0.5%, including at 24 keV where the high precission point by Block et al.(10) was taken into account by Fu and Perey only after tripling the quoted uncertainty.

Above 2 MeV the uncertainties in the differential scattering distributions increase, specifically in ranges of strongly interfering resonances.

ENDF/B-V represents an evaluation of $^{12}C$. The cross section of $^{13}C$ is very similar except in ranges of resonances in $^{12}C$ and $^{13}C$. Measurements on $^{13}C$ were carried out by Cohn et al.(18), Auchampangh et al.(19) and Poenitz et al.(17). The use of carbon as a standard below 1 MeV requires consideration of the $^{13}C$ resonances at ≈0.15 and 1.75 MeV.

## III. CONCLUSIONS and RECOMMENDATIONS

1. The total cross section of $^{12}C$ away from sharp resonances is well known below 2 MeV where it is a smooth function of energy. In view of remarkably larger and embarrassing discrepancies in total cross sections up to version V of ENDF/B, the measurement of $\sigma_{tot}$ ($^{12}C$) is recommended as a check in other total cross section experiments. Thus $^{12}C(n,n)$ should serve as a verification standard that is much easier to use than the H(n,n) standard which requires compound samples.

2. With exception of small forward and large backward angles the differential scattering cross section is known to 1-2% and recommended as a scattering standard below 2 MeV. Above 2 MeV the accuracy of C(n,n) results deteriorates and

## III. CONCLUSIONS and RECOMMENDATIONS (cont.)

a compromise between the relative ease of use contrasted to the better known H(n,n) will have to be made.

3. Evaluations exclude or ignore the presence of $^{13}C$ in natural carbon. Inclusion of $^{13}C$ in an evaluated file of natural carbon is recommended.

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# Fast Neutron Capture of Gold

by

Said F. Mughabghab

May 4, 1979

## I. DESCRIPTION

Because of its monoisotopic nature, its chemical purity, its large thermal neutron capture cross section and capture resonance integral, and the simple decay scheme of the product nucleus formed by neutron capture, the capture cross section of gold has become one of the basic standards.

## II. STATUS

Measurements prior to 1975 have been incorporated into an ENDF/B-V evaluation(1). Description of the data sets which thence appeared in the literature are the following.

A) The radiative capture cross section at 590 keV was measured(2) by the activation method. The neutron source is the T(p,n) $^3$He reaction. The $\gamma$-ray activity was determined by a Ge-Li detector. The neutron flux was measured by two different types of hydrogen gas counters. The results are summarized in Table 1. These results are to be compared with an ENDF/B-V value of 117 mb at 595 keV.

B) Konokov et al.,(3) measured the capture cross section of Au (along with $^{115}$In, $^{181}$Ta, $^{147,149}$Sm, Sm and $^{151,153}$Eu, Eu) in the energy range 3-350 keV. The neutron source is the $^7$Li(p,n) $^7$Be reaction. The capture events were detected by a spherical liquid scintillator of diameter 32 cm, filled with heavy hydrogen-free scintillator. The relative flux was measured by a $^{10}$B plate viewed by Na I(Tℓ) crystal. The capture cross section was normalized to a value of 596±24 mb at 30 keV. The data are in the form of curves and are as yet unavailable. A total error of 5.75% is assigned(3) to the capture cross section. There is good agreement (within 5%) with the measurements of Macklin et al., LeRigoleur, and Poenitz over the entire energy range(1).

C) Joly et al.(4), measured the capture cross section of Au in the energy range 0.5-2.5 MeV. The prompt capture γ-ray spectra were detected with a NaI spectrometer composed of a central and an annulus detector. The spectrometer is used in the anti-Compton and first-escape modes simultaneously, thus reducing the background. The capture spectra were extrapolated to zero energy. The flux of the neutrons was monitored by a plastic scintillator, a calibrated directional long counter, and a proton recoil telescope.

The results of these measurements are summarized in Table 2 and are compared with the ENDF/B-V evaluation. In Figs. 1-2, a comparison is made between the present and previous measurements and the ENDF/B-V evaluation.

Using the same technique, Drake et al.(4), reported at the 1977 Kiev Conference measurements at 0.720 and 3.00 MeV neutron energies. The preliminary value at 3.00 MeV is 21.4±3.5 mb. It is not clear whether this value is withheld by the authors in their subsequent publication(5).

D) Gupta et al.(6), employed a large Gd-loaded (0.5%) Liquid (NE 323) scintillator to measure the capture cross section of $^{197}$Au as well as $^{238}$U at three energy points: 1.68, 1.93, and 2.44 MeV. The prompt capture γ-rays were separated from the delayed γ-rays due to the thermalized neutrons by timing techniques. The relative neutrons produced by the T(p,n)$^3$He reaction were monitored by a directional counter. Since the efficiencies of both the neutron flux monitor and the liquid scintillator were not determined, the authors(6) normalized the sum of the cross sections to those of Lindner et al.(1), in the same energy region. It is felt by the present reviewer that this procedure is not totally justifiable. The results of the measurements are indicated in Table 3 and are compared with other measurements as well as those of the ENDF/B-V evaluation in Fig. 2.

E) More recently Macklin(7) remeasured the capture cross sections of gold with an attempt to extend the energy region up to 2.0 MeV (not yet analyzed).

## III. CONCLUSIONS and RECOMMENDATIONS

The recent published Au capture measurements are summarized in Tables 1, 2, 3, and compared with the ENDF/B-V evaluation in Figs. 1 and 2. As shown, particularly in Fig. 2, the recent measurements agree with the ENDF/B-V evaluation within the error limits. It will be of interest in the future to incorporate the Macklin data when they become available for the purpose of resolving the discrepancy between the Liskien and the Poenitz data sets. (Fig. 2).

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Table 1

| Counter Type | Neutron Energy (keV) | Cross Section (mb) | Total Error % | Neutron Flux Error % | Error in determining activity % |
|---|---|---|---|---|---|
| 1 | 597±16 | 125.5±4.1 | 3.3 | 2.2 | 1.4 |
| 2 | 590±23 | 121.2±4.1 | 3.4 | 2.2 | 1.2 |

Table 2

| Neutron energy (MeV) | Neutron energy spread (MeV) | Detection mode | Cross Section (mb) | Cross Section (weigthed mean) (mb) | ENDF/B-V (mb) |
|---|---|---|---|---|---|
| 0.52 | ± 0.08 | FE<br>AC | 132 ± 10<br>132 ± 9 | 132 ± 11 | 130.0 |
| 0.72 | ± 0.08 | FE<br>AC | 100 ± 9<br>102 ± 7 | 101 ± 9 | 98.7 |
| 0.94 | ± 0.07 | FE<br>AC | 71 ± 11<br>79 ± 7 | 77 ± 8 | 84.5 |
| 2.50 | ± 0.06 | FE<br>AC | 42 ± 6<br>41 ± 4 | 41 ± 6 | 37.5 |

AC = Anti-Compton mode

FE = First Escape mode

Tables (cont.)

Table 3

| $E_n$(MeV) | $\sigma_{n\gamma}$(mb)<br>Ref. 5 | $\sigma_{n\gamma}$(mb)<br>ENDF/B-V |
|---|---|---|
| 1.68 ± 0.03 | 59 ± 4 | 63.4 |
| 1.93 ± 0.03 | 55 ± 4 | 58.9 |
| 2.44 ± 0.03 | 45 ± 4 | 39.0 |

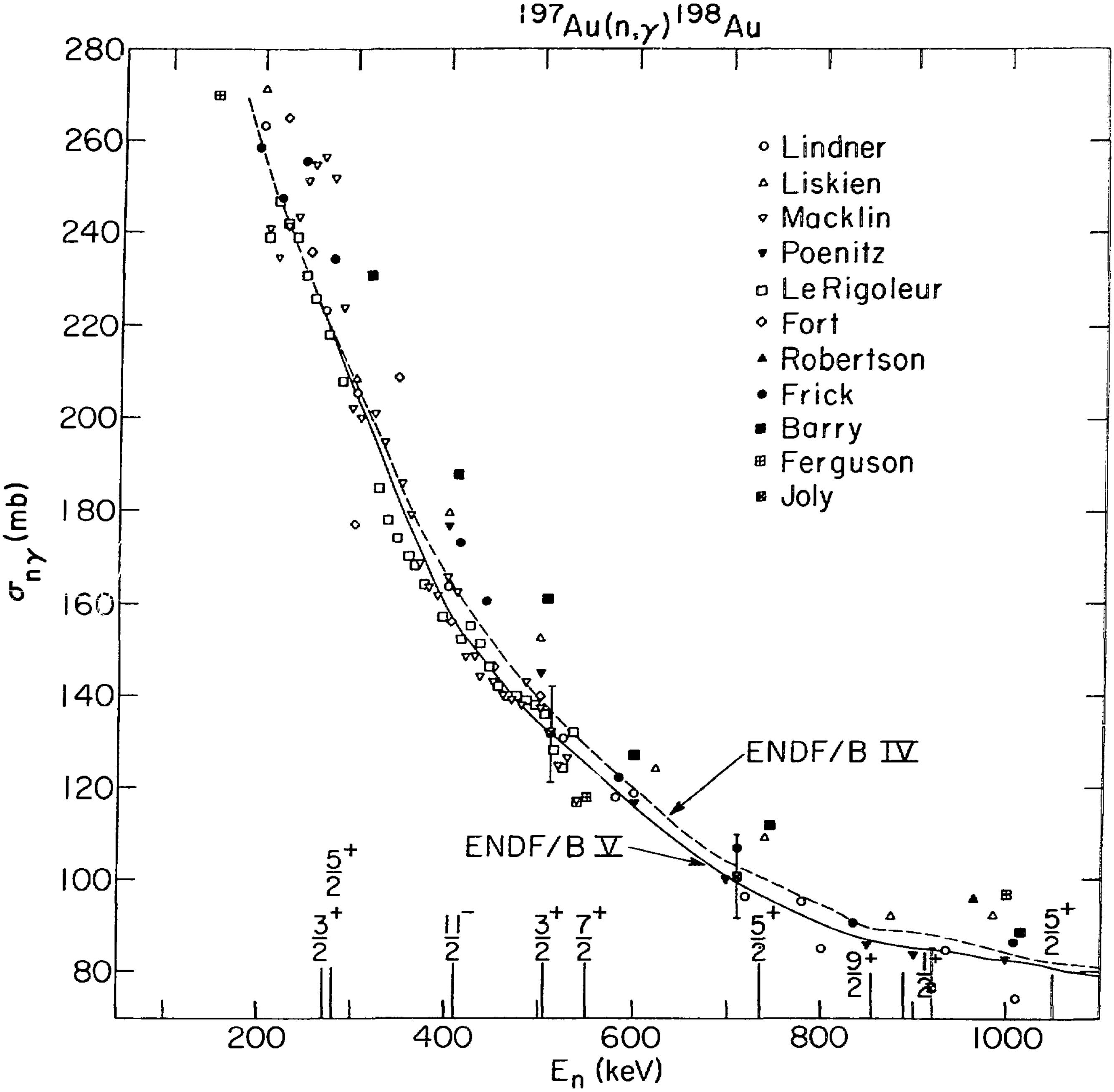

Fig. 1 The Capture Cross Section of Au in the Energy Region 200-1000 keV. The Vertical Lines Represent the Thresholds for the Inelastic Channels.

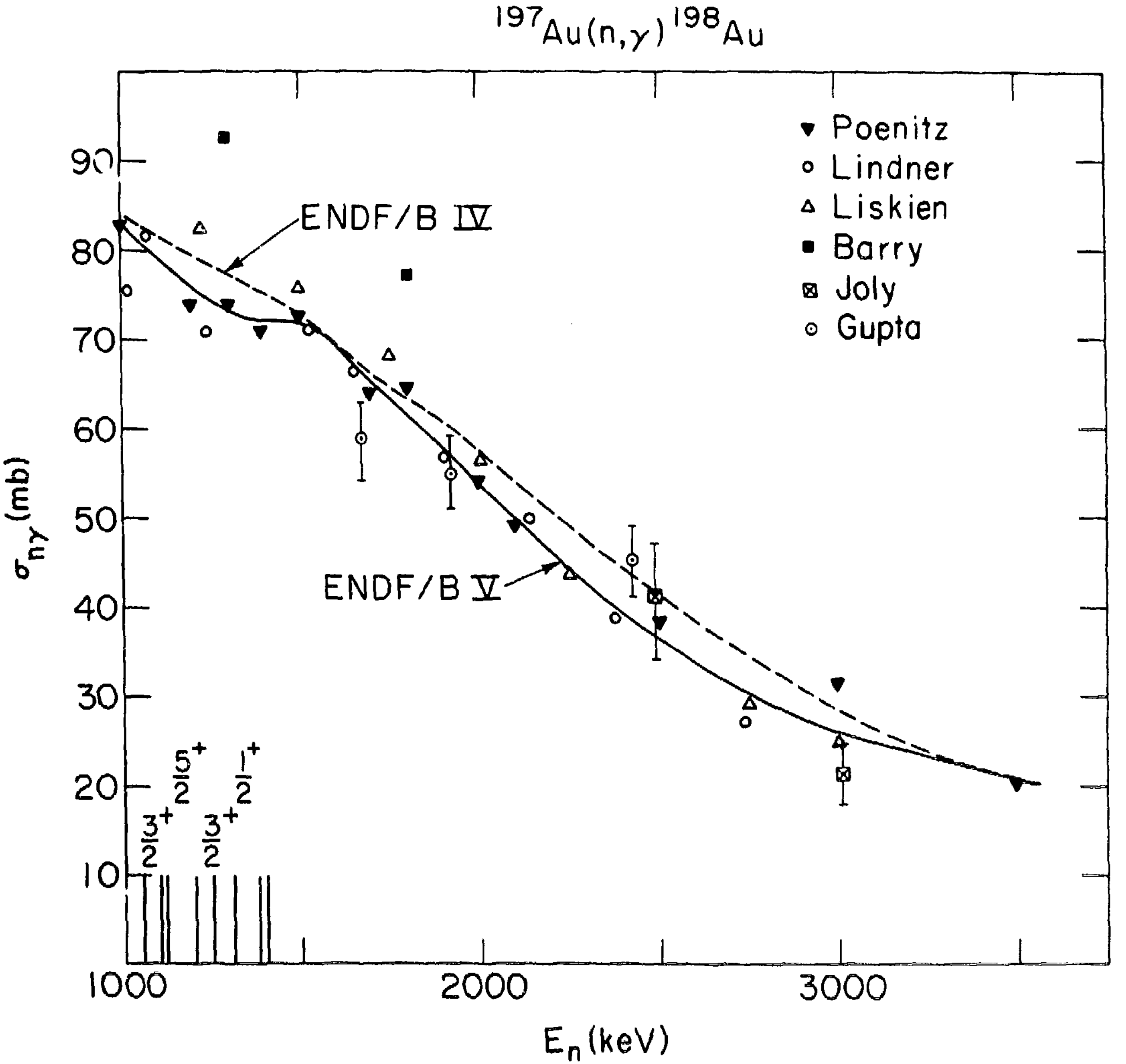

Fig. 2 Comparison of the ENDF/B-V Evaluation of the Capture Cross Section of Gold with Experimental Data.

# $^{235}$U FISSION CROSS SECTION

M.R. Bhat

June 11, 1979

## DESCRIPTION OF DATA AND ITS APPLICATION

Status of fission cross section of $^{235}$U from a few eV to 20 MeV will be discussed here. The data are needed for reactor applications. Because of the structure in the cross section its use as a standard is confined to about 100 keV and higher energies.

## NATURE OF DISCREPANCIES

### 1. Thermal to Epithermal Normalization:

It has been suggested by Bowman[1] and others that if the shape of $^{235}$U (n,f) cross section is determined over a wide energy range from thermal to a few hundred keV by using a linac, it could then be normalized to the accurately known thermal value. This program was followed in a recent evaluation[2] using currently available data and the results of this procedure and the nature of the discrepancy observed are discussed below.

Leonard[3] obtained $\sigma_f$ (0.0253 eV) = 583.54 ± 1.76b from a consistent evaluation of the thermal parameters of $^{235}$U. The data of Deruytter and Wagemans,[4] Czirr,[5] Gwin,[7] ORNL-RPI[9] and Bowmann[10] were normalized to this value and renormalized to the $^{6}$Li(n,$\alpha$) and $^{10}$B(n,$\alpha$) evaluations of Hale, et al.[11,12] (Table I). A weighted mean of the fission integral from 7.8 - 11 eV using these data was 241.2 ± 1.6 b-eV. Recent update of Czirr data[6] and a new measurement by Gwin[8] when included in the above give a weighted average of 242.7 ± 1.3 b-eV. Since the range of values used in these two averages is about 16 b-eV the errors in the averages are underestimated. The data that do not extend to thermal energies may be normalized to this integral to obtain a fission integral from 0.1 - 1.0 keV.

It is found that using the data of Gwin,[7] Czirr,[5] ORNL-RPI,[9] Wasson,[13] and Wagemans[14] a mean (unweighted) value for $I_{1.0\ \mathrm{keV}}^{0.1\ \mathrm{keV}} = 1.1998\mathrm{x}10^4$ b-eV is obtained. These data sets give values varying from $1.1474\mathrm{x}10^4$ b-eV to $1.2476\mathrm{x}10^4$ b-eV--a spread of about 9%. If the data at higher energies are normalized to this integral and then compared, they show a spread of about 14% at 10 keV.

Thus, these calculations show that the program of thermal normalization when continued into the epithermal region has problems with the shape differences of the different data sets; as these variations are much larger than the uncertainties claimed for each set. Hence, it would appear that it is necessary to have in addition to the thermal data and the 7.8 - 11 eV region, similar reference points at higher energies where accurate data are available for comparison of the different data sets. These reference points should extend high enough in energy so that they overlap van de Graaff data. Also, it appears that the systematic uncertainties of past measurements in the eV-keV range have been underestimated; again detailed studies over a wide energy range are required rather than relying on a few isolated intervals.

Plots of $^{235}$U(n,f) data from 100 keV to 20 MeV are shown in Figures 1-4 along with ENDF/B-IV and V evaluations.[15,16] In general, most of the data lie within ±3% about the ENDF/B-V evaluation. However, there appear to be the following problem areas where the data are discrepant.

### 2. The Minimum at 0.7 MeV

An examination of Figure 2 indicates that at or near this minimum the Käeppler[17] data are quite high; the U. of Michigan[18] datum of 1162 ± 25 mb is at 770 keV with the low point of 1101 ± 42 mb at 644 keV by Poenitz[19] and some of the Szabo,[20] Poenitz (black detector) points in between. The preliminary data of Wasson and Meier[21] fall on the associated activity as well as the grey detector data of Poenitz.[19] Though the error bars on the U. of Michigan and Poenitz data just overlap, there seems to be a problem as to how deep the minimum should be.

### 3. Shape at 0.95 MeV

From the present data (Figure 2) the rise of the cross section between 0.75-0.95 MeV as well as its shape in the neighborhood of 0.95 MeV (say 0.95-1.0 MeV) are not well determined. The questions one would like to see answered are: how sharp is the change in slope of the cross section at about 0.95 MeV and whether a local maximum as shown for example in the ENDF/B-V evaluation is justified. Answers to these questions may also provide clues to the underlying physical explanation of this feature of the cross section. More accurate data are needed to provide guidance in this respect.

### 4. Data Spread at 2.0 MeV

There appears to be a spread of about 9% in the data at the maximum at 2.0 MeV though most of the data lie in a 6% band. These include the shape data of Poenitz[19] (grey detector), and Leugers,[24] and the absolute measurements of Szabo,[20] Barton,[22] and Kari.[23]

### 5. Data Discrepancy 2.0-5.5 MeV

In this energy region (Figure 3) the Czirr, Barton, and Kari data appear to have a convex shape as opposed to the concave shape of the Szabo, Poenitz,[26] and Carlson[25] data. Carlson data are shape data only with the high energy set normalized to the low energy data from 2.8-3.2 MeV. Further, the Szabo, Poenitz, and Carlson data show good agreement in magnitude as well. The Kari data appear to be systematically higher than other measurements. The shape of the Barton data is such that it appears to lie diagonally across the band formed by the Kari and the Poenitz, Szabo, and Carlson data. The spread in these data is about 9% at 2.0 MeV, 11% at 4.0 Mev, and about 9% at 5.5 MeV. Some structure in the cross section is shown by the Carlson data between 4.0-4.5 MeV. Measurements to confirm this as well as to clear up the other discrepancies listed above are needed.

### 6. Data Shape and Magnitude 14-20 MeV

Both shape and magnitude of the fission cross section are discrepant in this energy range. Adamov[27] data at 14.8 MeV giving $\sigma_f = 2188 \pm 37$ mb and the Cancé[28] point at 14.6 MeV of $\sigma_f = 2063 \pm 39$ mb differ by 6%. Both the White[29] and Adamov data are in good agreement with Kari measurements. In this energy range, careful new absolute data are needed to resolve this discrepancy.

## COMMENTS AND RECOMMENDATIONS

The present status of $^{235}$U(n,f) data are such that most of the recent measurements lie within a ± 3% band about a mean. Specific problem areas with data have been listed above. Further work is needed to understand the experimental artifacts which give rise to these data discrepancies. When these effects are isolated and allowed for, more precise knowledge of this cross section will be possible.

## TABLE I

### $^{235}U$ Fission Integral from 7.8 - 11.0 eV

| Author [Ref] | $I_{7.8}^{11.0}$ (b-eV) |
|---|---|
| Deruytter and Wagemans [4] | 243.07 ± 2.43 |
| Czirr [5] | 240.57 ± 2.41 |
| Czirr [6] | 243.09 ± 1.94 |
| Gwin [7] | 235.92 ± 3.54 |
| Gwin [8] | 245 ± 3 |
| ORNL-RPI [9] | 241.30 ± 4.83 |
| Bowman [10] | 251.91 ± 7.56 |
| | |
| Weighted Average [Ref. 4,5,7,9,10] | 241.2 ± 1.6 |
| Weighted Average [Ref. 4,6,7-10] | 242.7 ± 1.3 |

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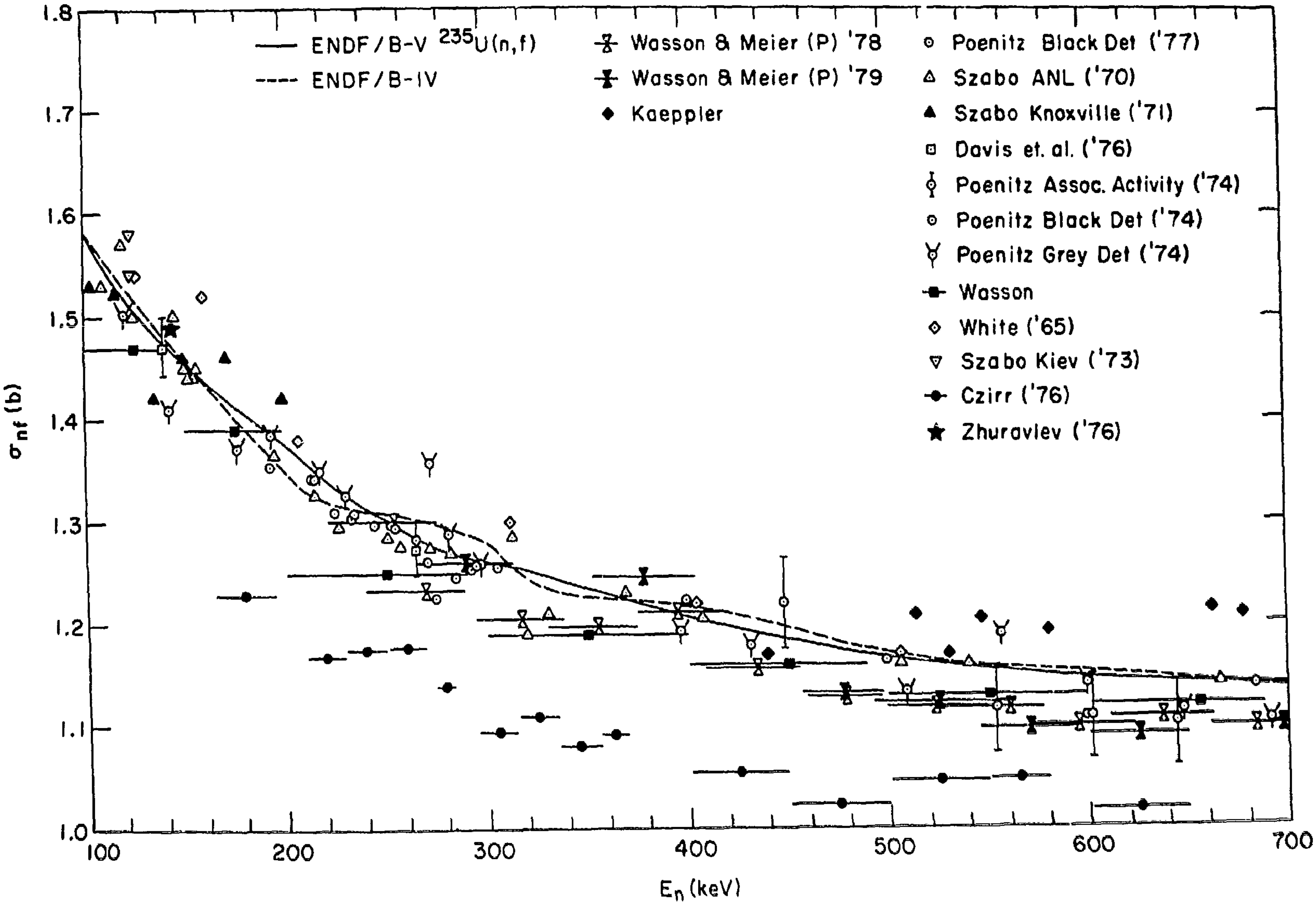

Figure 1. $^{235}$U(n,f) Cross Section from 100 to 700 keV

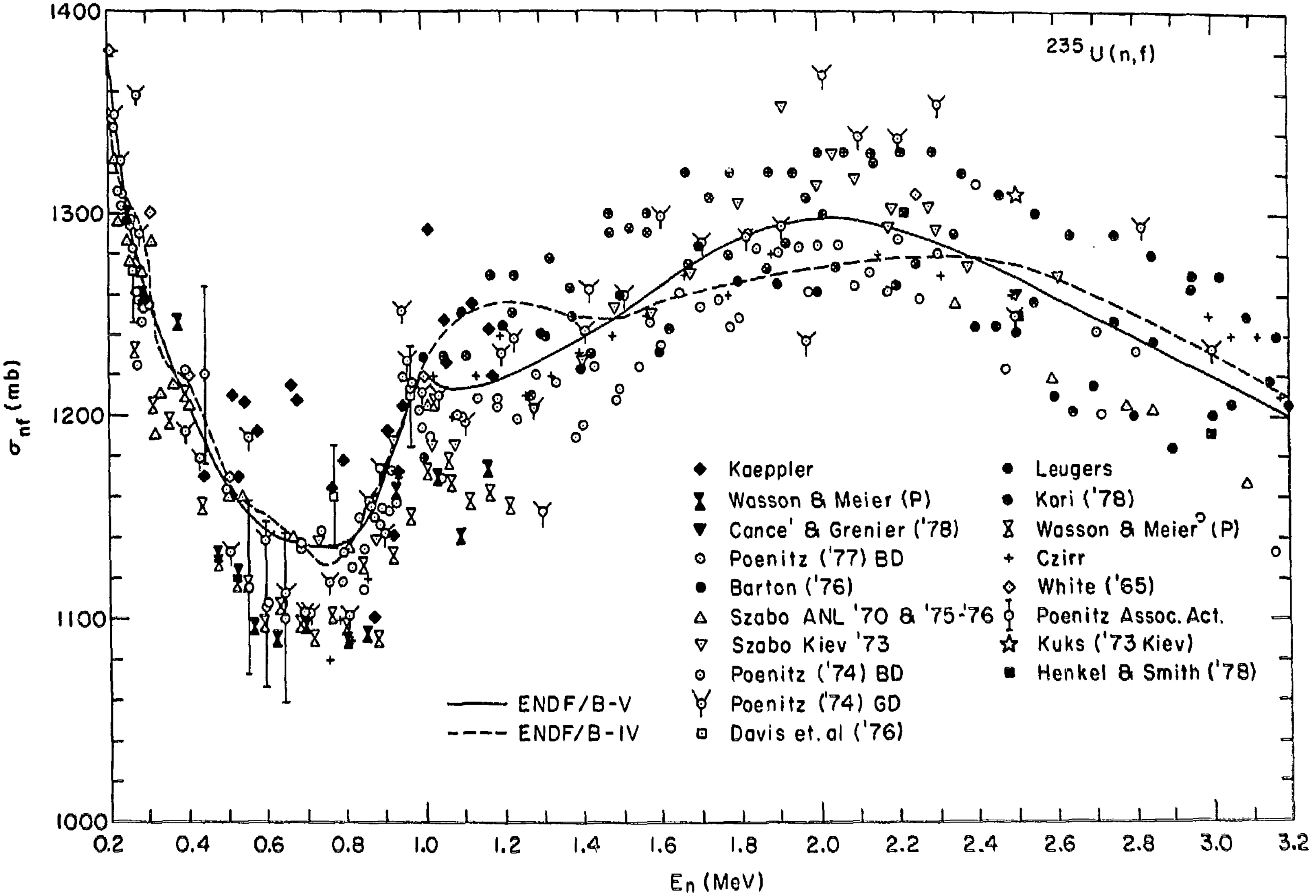

Figure 2. $^{235}$U(n,f) Cross Section from 0.2 to 3.2 MeV

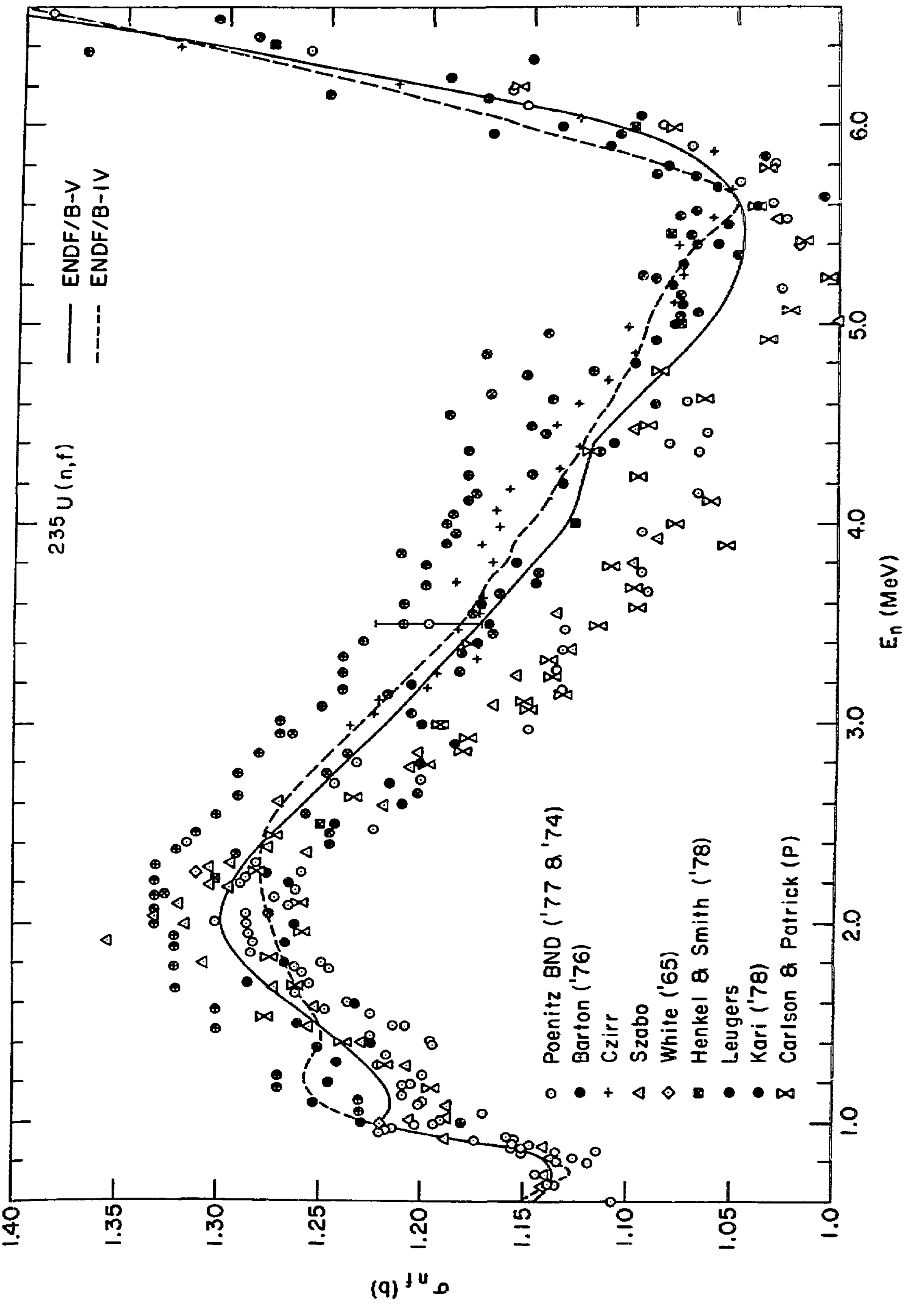

Figure 3. $^{235}U(n,f)$ Cross Section from 0.6 to 6.6 MeV

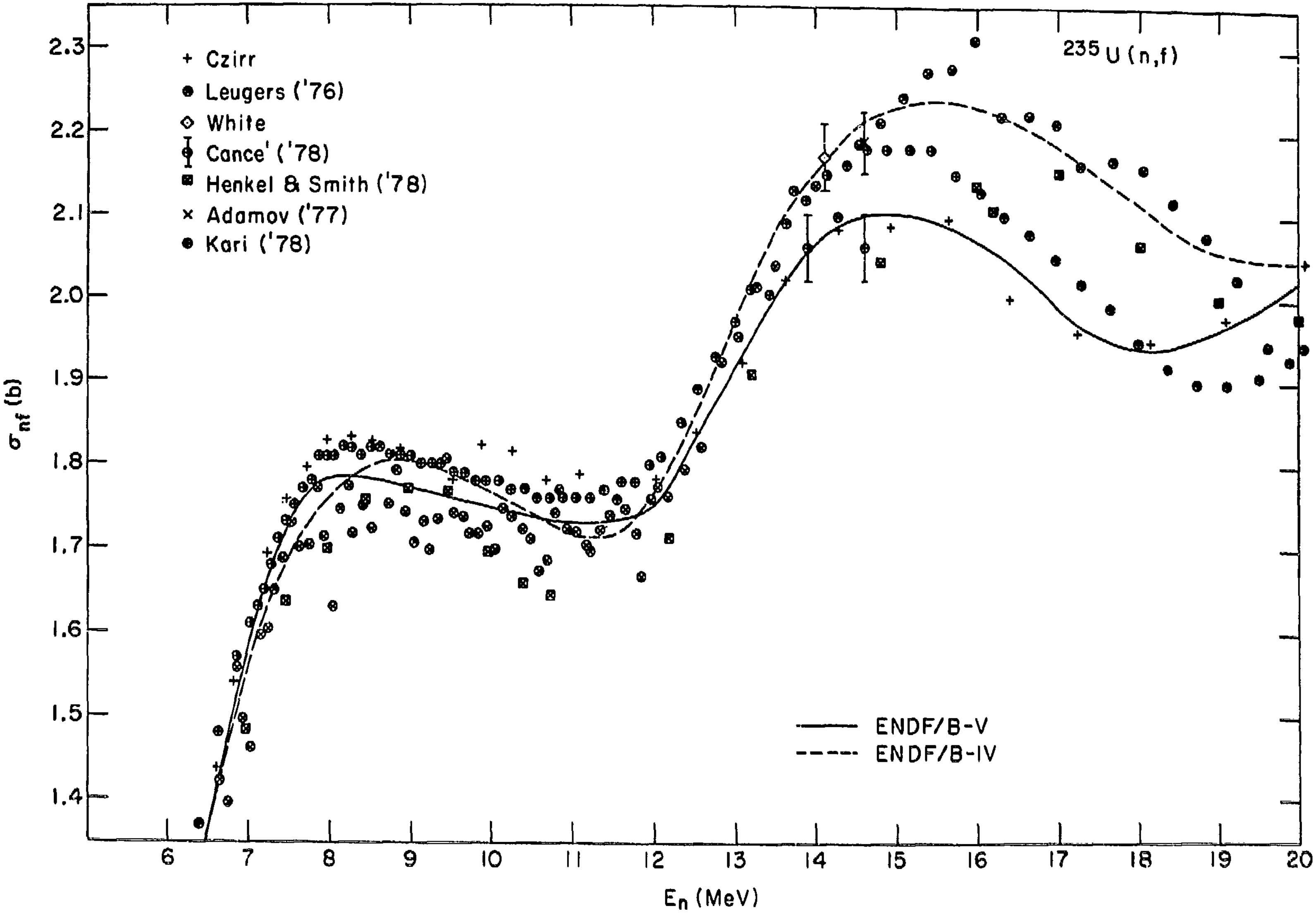

Figure 4. $^{235}$U(n,f) Cross Section from 6 to 20 MeV

# $\bar{\nu}$ of $^{252}$Cf (Spontaneous Fission)

J.R. Smith

July 16, 1979

## Description

$\bar{\nu}$ is the average number of neutrons emitted per fission event. The total $\bar{\nu}$ is the sum of the prompt and delayed components: $\bar{\nu} = \bar{\nu}_p + \bar{\nu}_d$. In time-gated experiments (e.g., liquid scintillators, the boron pile) it is $\bar{\nu}_p$ that is measured. Manganese bath measurements are of the total $\bar{\nu}$. The spontaneously fissioning $^{252}$Cf is the standard, from which $\bar{\nu}$ values for the fissile nuclei are determined by ratio measurements. Nearly all ratio measurements are comparisons of $\bar{\nu}_p$.

## Status

The discrepancy among measured values of $\bar{\nu}$ for $^{252}$Cf has long constituted one of the most vexing problems in the field of nuclear data interpretation. The high values obtained in a pair of measurements using large liquid scintillators(1,2) were challenged by the low value obtained from the Boron Pile(3). The low value found support from two measurements using the manganese bath technique.(4,5) A third liquid scintillator experiment(6) yielded an intermediate value.

A survey by Axton(7) in 1972 found a weighted average $\bar{\nu} = 3.734 \pm 0.008$ neuts/fission, using weights based on error estimates that were in some cases expanded from their original values. This weighted average was dominated by the lower values, since they were in general newer measurements with lower error estimates than the earlier liquid scintillator measurements. In 1977, a review by Boldeman(8) derived a recommended value $\bar{\nu} = 3.745 \pm 0.010$. The new information available to Boldeman included the results of a measurement by Bozorgmanesh,(9) using the manganese bath technique, plus revaluation upward of the Boron Pile value and Boldeman's own liquid scintillator value, both due to Monte Carlo calculations by Ullo(10,11) of neutron detection efficiencies. The recent summary by Smith(12) reveals three additional developments. These are as follows:

1. The manganese bath values of Axton and DeVolpi have each been revalued upward by approximately 0.5%. The Axton value becomes 3.743, as the result of accounting for the effects of impurities identified in the chemical analyses of the Axton bath performed at both NPL and

INEL. The DeVolpi value becomes 3.747 as a result of a more consistent procedure in extrapolating the experimental results to the condition of zero hydrogen content of the manganese bath. The average of the manganese bath results is now near 3.750. If the apparently discrepant White-Axton value is omitted, there is very tight agreement at $\bar{\nu}$ = 3.745.

2. Spencer(13) has measured $^{252}$Cf $\bar{\nu}_p$ using a large liquid scintillator, obtaining a value $\bar{\nu}_p$ = 3.783 ± 0.010. This value is slightly changed from the earlier reported value(12) 3.789 ± .007. This new result, having both a high value and a low error estimate, has a dramatic effect on a weighted average of all data. The total $\bar{\nu}$ weighted average becomes 3.766 ± .007.

This result illustrates the vulnerability of the weighted average to dominance by a single high-weight value. Where the presence of unresolved systematic effects is indicated, at least some of the error estimates must be considered suspect. The prerequisites for a meaningful weighted average are therefore not satisfied. Both the weighted average and the resultant error estimate must, under these conditions, be viewed with extreme caution.

3. Gwin's $\bar{\nu}_p$ ratio measurements(14) suggest the presence of a foil thickness effect in $\bar{\nu}_p$ ratio measurements. Gwin agrees with Boldeman's measurement of $\bar{\nu}_p(^{239}\mathrm{Pu})/\bar{\nu}_p(^{252}\mathrm{Cf})$, where both used $^{239}$Pu foil thickness of 100 μg/cm$^2$. For $^{235}$U, however, where Gwin again used a foil of 100 μg/cm$^2$ thickness, his $\bar{\nu}$ ratio is 0.8% higher than that of Boldeman, who used a foil whose thickness was near 800 μg/cm$^2$. This difference does not affect the $^{252}$Cf $\bar{\nu}$ values per se, but it directly affects the derived values of $\bar{\nu}$ for the fissile nuclei, as well as the indication of a discrepancy between $\bar{\nu}$ and η.

The $\bar{\nu}$ values for ENDF/B Version IV were established using $^{252}$Cf $\bar{\nu}$ = 3.757, and weighted averages of the $\bar{\nu}$ ratio measurements. For Version V the weighted average, $\bar{\nu}$ = 3.766, from Smith's paper was adopted, along with $\bar{\nu}$ ratios based on Gwin's measurement for $^{235}$U, plus the assumption that Boldeman's lower ratio value was due to a foil thickness effect that is linear with foil thickness.

The current status of $\bar{\nu}$ values is illustrated in Table I.

## Conclusions and Recommendations

The value of $^{252}$Cf $\bar{\nu}$ appears now to be moving away from the low value that was favored in past analyses. Additional work is required to confirm this trend.

The assumptions made relative to Boldeman's $\bar{\nu}$ ratio measurements remain to be confirmed. Boldeman himself does not agree with the interpretation, citing data by Condé and Diven to the contrary. However, there is doubt that the Condé data should be interpreted as precluding an appreciable effect in the Boldeman measurement. Edward Melkonian and his graduate student, Farhad Conhensedgh, at Columbia University, are attempting a quantitative calculation of the foil thickness effect in Boldeman's experiment, using their computer code BIASX. Confirmation of the magnitude of the foil thickness effect would register an impact on the $\bar{\nu}(E)$ data as well as on the thermal $\bar{\nu}$ values for the fissile nuclei.

Two $^{252}$Cf $\bar{\nu}$ measurements are still in progress. Spencer is planning a new run with his liquid scintillator, using a small diameter thru-tube and a less massive proton recoil detector for the efficiency calibration. The manganese bath measurement by Smith at INEL is nearing completion, with variations of bath concentration yet to be performed. Preliminary indications are that the result may be near 3.75, leaving a substantial gap between the results of the two newest measurements.

Herbert Goldstein is using his "pointwise" version of ANISN to calculate details of neutron transport and absorption in the manganese bath. Preliminary results suggest that these calculations will provide the best description to date of the effects of absorption due to (n,p) and (n,$\alpha$) reactions in sulfur and oxygen. They are also to include the effects of leakage and manganese resonance absorption.

A limitation on the manganese bath technique lies in the fact that only absorptions in manganese are detected. Absorptions or losses elsewhere in the system must be accounted for by calculation using evaluated cross sections and measured bath compositions, or by measurement in auxiliary experiments. As refinements are made in the method, uncertainties in cross sections assume a larger importance. A case in point is sulfur. The correction for sulfur absorption is about 4% in a manganese bath. With the usually quoted thermal absorption value of 520 ± 30 mb, the sulfur uncertainty alone can contribute about a quarter percent to the manganese bath measurement. New sulfur cross section data of higher accuracy are needed all along the line from thermal absorption, through epithermal capture, to the (n,$\alpha$) and (n,p) cross section data.

Perhaps the most puzzling aspect of the $\bar{\nu}$ picture at present is the difference between results from the two most recent liquid scintillator measurements. A strong effort should be made to identify a reason for the difference between the Boldeman and Spencer values. The liquid scintillator measurements are highly dependent upon Monte Carlo calculations in the interpretation of the experimental data. Although there are areas of agreement between Monte Carlo calculations, there are other areas where puzzling differences appear. The Monte Carlo techniques and the cross sections used in the various calculations should be closely scrutinized.

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## Table I

### $^{252}$Cf $\bar{\nu}_t$ Summary

| | 1972 Status | Current Status | Group Ave. |
|---|---|---|---|
| **Liquid Scintillator** | | | |
| Spencer(34) | | 3.792 ± 0.011 | |
| Boldeman(33,19) | 3.744 ± 0.014 | 3.755 ± 0.016 | |
| Asplund-Nilsson(37) | 3.778 ± 0.060 | 3.792 ± 0.040 | |
| Hopkins-Diven(36) | 3.770 ± 0.031 | 3.777 ± 0.031 | 3.780 ± .009 |
| **Manganese Bath** | | | |
| Axton (9) | 3.725 ± 0.019 | 3.743 ± 0.019 | |
| DeVolpi (7) | 3.729 ± 0.030 | 3.747 ± 0.019 | |
| Bozorgmanesh (28) | | 3.744 ± 0.023 | |
| White, Axton (27) | 3.797 ± 0.040 | 3.815 ± 0.040 | |
| Aleksandrov (29) | | 3.747 ± 0.036 | 3.750 ± .011 |
| **Boron Pile** | | | |
| Colvin (30) | 3.713 ± 0.015 | 3.739 ± 0.021 | |
| Overall Wtd. Ave: | 3.735 ± 0.008 | 3.766 ± 0.006 | |

# NEUTRON ENERGY STANDARDS

F. G. Perey

October 1979

## Description

Currently in ENDF/B we have no recommended "neutron energy standards." G. D. James reported[1] at the NBS Standards Conference of 1977 on the situation. Quoting from James: "Neutron energy standards are required to help ensure that all neutron spectrometers produce data on energy scales that agree to within the estimated errors of measurements. Discrepancies in neutron energy scales, of which there have been several examples in recent years, present additional problems for evaluators, and compilers, for users of data...."

## Status

The INDC Standards Subcommittee has considered the problem of establishing a list of neutron resonance energies which could be used as references in time-of-flight measurements. James in his paper lists some 40 resonances in the range of 0.65 eV to 12.1 MeV which might be suitable or worthy of consideration. Results from several different laboratories for a few resonances are intercompared. (The 244-keV resonance in $^{6}$Li, the 298-keV resonance in $^{23}$Na, the 2078-keV resonance in $^{12}$C, and five resonances in $^{238}$U from 145 to 2489 keV.) Most of the emphasis in James' paper is on time-of-flight spectrometers using white neutron sources. Meadows[2] has discussed the problems of neutron energy determination using "monoenergetic" neutron sources.

James for a few resonances attempts an evaluation of the energies based upon "unweighted" averages of reported results and determines the uncertainties from the spread of the data. It was pointed out at the Harwell Conference[3] that such a procedure is incorrect since it ignores the important correlations between the resonance energies determined in a single experiment and also those which exist between most results from a given laboratory. The procedure for determining the covariances in the energies in a given experiment and how to combine the data when we have covariances were explained and a few of the results from James' paper were used as illustration. Olsen *et al.*[4] have published a complete documentation of some resonance energies used by James in his NBS paper. Since then Cierjacks *et al.*[5] have reported some high precision energies for resonances in $^{12}$C and $^{16}$O in the range of 3 to 15 MeV.

With very few exceptions most papers do not report sufficient details in the experiments performed to establish the correlations in the results and therefore an evaluation cannot be done properly.

Using the information in Olsen *et al.*'s paper[4] and James' paper,[1] the covariance matrices of these data were determined and the results combined using the method described at Harwell.[3] The enclosed Table I gives the energies obtained and their standard deviations, Table II provides the correlation matrix. The covariance matrices of these ORELA and Harwell Synchrocyclotron data could be easily documented so that correlations with future results from these laboratories could be obtained.

## Conclusions and Recommendations

Some problems of data intercomparison and evaluation could be greatly alleviated if a consistent set of neutron resonance energies was made available to measurers and evaluators. There does not exist such a documented set of energies today, but with a minimum amount of effort we believe that one could be established, and the results given in Tables I and II may be used as a start.

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Table I. Evaluated Neutron Resonance Energies.

| | | This Evaluation | | James | |
|---|---|---|---|---|---|
| Energy Range (eV) | Isotope | Resonance Energy (eV) | Std. Dev. (eV) | Resonance Energy (eV) | Std. Dev. (eV) |
| 1-10 | U-238 | 6.6713 | .0007 | 6.672 | |
| 10-100 | U-238 | 10.235 | .0022 | 10.236 | |
| | U-238 | 20.862 | .0021 | 20.864 | |
| | U-238 | 36.667 | .0036 | 36.671 | |
| | U-238 | 66.008 | .0065 | 66.015 | |
| | U-238 | 80.721 | .0082 | 80.729 | |
| 100-1000 | U-238 | 145.620 | .013 | 145.617 | .033 |
| | U-238 | 165.249 | .015 | | |
| | U-238 | 189.628 | .016 | 189.64 | |
| | U-238 | 237.324 | .020 | | |
| | U-238 | 290.941 | .025 | | |
| | U-238 | 311.248 | .034 | 311.18 | .25 |
| | U-238 | 397.538 | .040 | 397.58 | |
| | U-238 | 463.089 | .046 | 463.18 | .24 |
| | U-238 | 619.886 | .063 | 619.95 | |
| | U-238 | 709.196 | .070 | 708.22 | .20 |
| | U-238 | 904.971 | .075 | 905.03 | |

Table I. Evaluated Neutron Resonance Energies (cont.)

| | | This Evaluation | | James | |
|---|---|---|---|---|---|
| Energy Range (eV) | Isotope | Resonance Energy (eV) | Std. Dev. (eV) | Resonance Energy (eV) | Std. Dev. (eV) |
| 1000-10000 | U-238 | 1419.67 | .12 | 1419.88 | .32 |
| | U-238 | 1473.72 | .12 | 1473.8 | |
| | U-238 | 1637.96 | .14 | | |
| | U-238 | 2030.36 | .17 | | |
| | U-238 | 2145.42 | .18 | | |
| | U-238 | 2489.02 | .21 | 2489.47 | .50 |
| | U-238 | 2672.04 | .22 | 2672.2 | |
| | U-238 | 2865.20 | .24 | | |
| | U-238 | 3205.60 | .27 | | |
| | Pb-206 | 3357.18 | .30 | 3360 | 10. |
| | U-238 | 3457.91 | .29 | 3458.1 | |
| | U-238 | 3573.80 | .30 | | |
| | U-238 | 4512.00 | .38 | 4512.0 | |
| | U-238 | 5650.22 | .47 | 5650.6 | |
| | Al-27 | 5903.11 | .57 | 5903 | 8. |
| (keV) | | (keV) | (keV) | (keV) | (keV) |
| 10-100 | S-32 | 30.376 | .0041 | 30.378 | .006 |
| | Na-23 | 53.187 | .026 | 53.191 | .027 |
| | Si-28 | | | 67.73 | .02 |
| | Pb-206 | 71.186 | .016 | 71.191 | .018 |
| | Fe-56 | | | 90.134 | .016 |
| | S-32 | 97.498 | .016 | 97.512 | .028 |
| | S-32 | 112.175 | .020 | 112.186 | .033 |

## Table II. Correlation Coefficients (X100).

| Res. Energy (eV) | 6.67 | 10.23 | 20.86 | 36.67 | 66.01 | 80.72 | 145.6 | 165.2 | 189.6 | 237.3 | 290.9 | 311.2 | 397.5 | 463.1 | 619.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.67 | 100 | | | | | | | | | | | | | | |
| 10.23 | 42 | 100 | | | | | | | | | | | | | |
| 20.86 | 92 | 42 | 100 | | | | | | | | | | | | |
| 36.67 | 94 | 44 | 97 | 100 | | | | | | | | | | | |
| 66.01 | 94 | 44 | 97 | 97 | 100 | | | | | | | | | | |
| 80.72 | 92 | 42 | 94 | 94 | 97 | 100 | | | | | | | | | |
| 145.6 | 56 | 27 | 58 | 58 | 58 | 58 | 100 | | | | | | | | |
| 165.2 | 57 | 26 | 57 | 59 | 59 | 57 | 88 | 100 | | | | | | | |
| 189.6 | 57 | 26 | 59 | 59 | 59 | 59 | 88 | 90 | 100 | | | | | | |
| 237.3 | 59 | 28 | 59 | 61 | 61 | 59 | 90 | 90 | 93 | 100 | | | | | |
| 290.9 | 59 | 28 | 59 | 61 | 61 | 59 | 90 | 90 | 93 | 95 | 100 | | | | |
| 311.2 | 84 | 39 | 87 | 87 | 87 | 87 | 51 | 53 | 53 | 55 | 55 | 100 | | | |
| 397.5 | 92 | 42 | 92 | 94 | 94 | 92 | 58 | 57 | 56 | 59 | 59 | 84 | 100 | | |
| 463.1 | 92 | 42 | 92 | 94 | 94 | 92 | 56 | 57 | 57 | 59 | 59 | 84 | 92 | 100 | |
| 619.9 | 89 | 42 | 92 | 92 | 94 | 92 | 55 | 57 | 56 | 59 | 59 | 84 | 89 | 89 | 100 |
| 709.2 | 92 | 42 | 94 | 94 | 94 | 92 | 58 | 57 | 59 | 59 | 59 | 84 | 91 | 92 | 91 |
| 905.0 | 59 | 28 | 61 | 61 | 61 | 61 | 90 | 93 | 95 | 95 | 95 | 54 | 60 | 61 | 58 |
| 1420. | 58 | 27 | 58 | 60 | 60 | 58 | 88 | 88 | 90 | 93 | 93 | 54 | 57 | 58 | 58 |
| 1474. | 59 | 28 | 61 | 61 | 61 | 61 | 90 | 93 | 93 | 95 | 95 | 54 | 58 | 59 | 58 |
| 1638. | 59 | 28 | 61 | 61 | 61 | 61 | 90 | 93 | 93 | 95 | 95 | 54 | 61 | 59 | 58 |
| 2030. | 60 | 26 | 59 | 62 | 62 | 59 | 90 | 90 | 93 | 93 | 95 | 55 | 59 | 59 | 59 |
| 2145. | 59 | 28 | 62 | 61 | 61 | 61 | 90 | 93 | 95 | 95 | 95 | 55 | 61 | 59 | 58 |
| 2489. | 59 | 28 | 62 | 61 | 61 | 61 | 90 | 93 | 93 | 95 | 95 | 54 | 58 | 59 | 58 |
| 2672. | 59 | 28 | 61 | 61 | 61 | 61 | 90 | 93 | 93 | 95 | 95 | 54 | 58 | 59 | 58 |
| 2865. | 57 | 26 | 59 | 59 | 59 | 59 | 88 | 90 | 90 | 93 | 93 | 52 | 59 | 59 | 59 |
| 3206. | 59 | 28 | 59 | 61 | 61 | 59 | 90 | 93 | 93 | 95 | 95 | 54 | 58 | 59 | 58 |
| 3357 | 55 | 26 | 57 | 57 | 57 | 57 | 86 | 88 | 88 | 90 | 90 | 53 | 57 | 57 | 57 |
| 3458 | 59 | 28 | 59 | 61 | 61 | 61 | 90 | 93 | 93 | 95 | 95 | 95 | 58 | 59 | 58 |

## Table II. Correlation Coefficients (cont.)

| Res. Energy (eV) | 709.2 | 905.0 | 1420 | 1474 | 1638 | 2030 | 2145 | 2489 | 2672 | 2865 | 3206 | 3357 | 3458 | 3574 | 4512 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 709.2 | 100 | | | | | | | | | | | | | | |
| 905.0 | 61 | 100 | | | | | | | | | | | | | |
| 1420 | 58 | 95 | 100 | | | | | | | | | | | | |
| 1474 | 61 | 97 | 92 | 100 | | | | | | | | | | | |
| 1638 | 61 | 97 | 92 | 97 | 100 | | | | | | | | | | |
| 2030 | 59 | 97 | 92 | 95 | 97 | 100 | | | | | | | | | |
| 2145 | 61 | 97 | 95 | 97 | 97 | 97 | 100 | | | | | | | | |
| 2489 | 61 | 97 | 93 | 97 | 97 | 97 | 97 | 100 | | | | | | | |
| 2672 | 61 | 97 | 93 | 97 | 97 | 97 | 97 | 97 | 100 | | | | | | |
| 2865 | 59 | 95 | 92 | 95 | 95 | 95 | 97 | 95 | 95 | 100 | | | | | |
| 3206 | 61 | 97 | 93 | 97 | 97 | 95 | 97 | 97 | 97 | 95 | 100 | | | | |
| 3357 | 57 | 92 | 88 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 92 | 100 | | | |
| 3458 | 61 | 97 | 95 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 92 | 100 | | |
| 3574 | 61 | 97 | 95 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 97 | 92 | 97 | 100 | |
| 4512 | 59 | 98 | 93 | 98 | 97 | 95 | 97 | 97 | 97 | 95 | 97 | 92 | 97 | 97 | 100 |
| 5650 | 59 | 98 | 93 | 98 | 98 | 95 | 98 | 97 | 97 | 95 | 97 | 92 | 97 | 97 | 97 |
| 5903 | 52 | 84 | 79 | 84 | 84 | 81 | 83 | 83 | 83 | 83 | 83 | 79 | 83 | 86 | 83 |
| 30376 | 30 | 50 | 47 | 50 | 50 | 49 | 51 | 51 | 51 | 51 | 51 | 49 | 53 | 53 | 52 |
| 53187 | 10 | 15 | 15 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| 71186 | 20 | 34 | 34 | 36 | 35 | 35 | 35 | 37 | 37 | 35 | 37 | 35 | 37 | 37 | 38 |
| 97498 | 21 | 34 | 34 | 35 | 35 | 35 | 35 | 36 | 36 | 36 | 36 | 35 | 36 | 37 | 38 |
| 112175 | 20 | 32 | 31 | 32 | 33 | 33 | 33 | 33 | 34 | 33 | 34 | 33 | 35 | 35 | 36 |

Table II. Correlation Coefficients (cont.)

| Res. Energy (eV) | 6.67 | 10.23 | 20.86 | 36.67 | 66.01 | 80.72 | 145.6 | 165.2 | 189.6 | 237.3 | 290.9 | 311.2 | 397.5 | 463.1 | 19.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3574 | 59 | 28 | 59 | 61 | 61 | 61 | 91 | 93 | 93 | 95 | 95 | 55 | 58 | 59 | 58 |
| 4512 | 60 | 26 | 60 | 62 | 62 | 59 | 91 | 91 | 93 | 95 | 95 | 55 | 59 | 60 | 59 |
| 5650 | 57 | 26 | 60 | 59 | 62 | 59 | 88 | 91 | 93 | 93 | 95 | 55 | 59 | 60 | 59 |
| 5903 | 50 | 23 | 50 | 52 | 52 | 50 | 77 | 77 | 79 | 79 | 82 | 46 | 49 | 50 | 50 |
| 30376 | 28 | 14 | 29 | 31 | 31 | 29 | 45 | 44 | 46 | 47 | 47 | 27 | 30 | 30 | 30 |
| 53187 | 9 | 4 | 9 | 8 | 8 | 8 | 13 | 13 | 13 | 13 | 15 | 9 | 8 | 8 | 8 |
| 71186 | 19 | 9 | 19 | 19 | 19 | 19 | 30 | 29 | 31 | 31 | 31 | 18 | 20 | 21 | 20 |
| 97498 | 19 | 9 | 19 | 19 | 19 | 19 | 30 | 30 | 31 | 31 | 31 | 19 | 21 | 21 | 21 |
| 112175 | 18 | 9 | 17 | 17 | 17 | 17 | 28 | 28 | 28 | 29 | 29 | 18 | 19 | 19 | 19 |

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|  | 5650 | 5903 | 30376 | 53187 | 71186 | 97498 | 112175 |
|---|---|---|---|---|---|---|---|
| 5650 | 100 |  |  |  |  |  |  |
| 5903 | 86 | 100 |  |  |  |  |  |
| 30376 | 52 | 46 | 100 |  |  |  |  |
| 53187 | 17 | 15 | 11 | 100 |  |  |  |
| 71186 | 38 | 34 | 26 | 10 | 100 |  |  |
| 97498 | 39 | 34 | 32 | 9 | 21 | 100 |  |
| 112175 | 37 | 32 | 31 | 8 | 21 | 34 | 100 |

# THERMAL FISSILE PARAMETERS

PLANNED TO BE INCLUDED AT A LATER DATE.

# SECTION B: IMPORTANT ACTINIDE NUCLEAR DATA

SECTION B: IMPORTANT ACTINIDE NUCLEAR DATA

# $^{235}$U Resonance Fission Integral and Alpha Based on Integral Measurements

J. Hardy, Jr.

July 17, 1979

## DESCRIPTION

The U-235 resonance integrals for fission ($I_F$) and capture ($I_C$) are of prime importance in analyzing the performance of thermal reactors. They also significantly affect inferences about the U-235 fission spectrum obtained from analysis[1] of homogeneous aqueous U-235 critical experiments. This comes about because the high-leakage assemblies, for which $k_{eff}$ is sensitive to the fission spectrum, also have low H/U ratios and hence hard flux spectra (which makes them sensitive to U-235 $I_F$ and $I_C$). The uncertainties are also important - especially the uncertainty of resonance alpha in drawing conclusions about the fission spectrum from critical assemblies.

## STATUS

The integral results for U-235, as summarized by Reynolds,[2] comprise eight measurements of $I_F$ and three measurements of resonance alpha from which $I_C$ is derived. A discussion of experimental methods was given by Feiner and Esch.[3]

A weighted average of the eight integral results gives 274 ± 5 b for $I_F$ (> 0.5 eV). This includes a common normalization uncertainty of which the main component is the uncertainty in the gold resonance integral, taken to be 1.4% (see Ref. 4). The 275 ± 5 b value of $I_F$ quoted in BNL-325[5] appears to be based on very similar considerations.

The integral experiments give an $\alpha(> 0.5 \text{ eV}) = 0.513$ (see Ref. 2). The uncertainty is approximately 0.015.

ENDF/B-IV and V are based on differential experiments. Comparisons of the two files are given below.

| | Version IV (Ref. 6) | Version V (MAT 1395, File 1) |
|---|---|---|
| $I_F$ | 282 b | 281.7 b |
| $I_C$ | 137.7 b | 139.2 b |
| $\alpha$ | 0.488 | 0.494 |

Thus, for ENDF/B-V, $I_F$ is 3% ± 2% above the integral experiments and alpha is 3.7% ± 3% below the integral experiments.

## CONCLUSIONS AND RECOMMENDATIONS

ENDF/B-V U-235, which is based on differential experiments, has a fission resonance integral 3% above the best integral-experimental value and a resonance alpha 3.7% below the best integral-experimental value. These differences lie just outside the uncertainties of the integral results. In view of the importance of $I_F$ and $I_C$ for thermal reactors, the capture and fission resonance cross sections should be re-evaluated with full consideration given to the integral experiments. Careful attention should also be given to evaluating the uncertainties in $I_F$, $I_C$, and alpha.

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# ALPHA, THE RATIO OF CAPTURE TO FISSION IN THE FISSILE ISOTOPES

L. W. Weston and M. S. Moore

July 18, 1979

## DESCRIPTION

The application of alpha is in thermal and fast reactors. This status report will cover only the major fissile isotopes; $^{233}$U, $^{235}$U, $^{239}$Pu, and $^{241}$Pu. Only differential measurements will be considered and the energy range considered is 0.5 eV to 500 keV.

## I. STATUS FOR $^{233}$U

A. RESOLVED RESONANCE REGION. The most extensive measurements of alpha are those of Weston et al.[1] over the neutron energy range from 0.4 to 2000 eV. The agreement with the data of Brooks et al.[2] in the neutron energy range up to 11 eV is essentially within experimental uncertainties. ENDF/B-V is based upon the data of Weston et al.[1]

B. UNRESOLVED RESONANCE REGION. ENDF/B-V is based upon the data of Weston et al.[1] up to 2000 eV. From 2000 to 30,000 eV there are essentially no data. The uncertainty in the data in the unresolved resonance region is too great to determine the variations in alpha as was done in the cases of the other major fissile isotopes.

C. FAST REGION. From 30 keV to 1 MeV there are measurements of alpha by Hopkins et al.[3] and Spivak et al.[4]

### CONCLUSIONS AND RECOMMENDATIONS FOR $^{233}$U

There is a complete lack of measurements from 2 to 30 keV. New measurements above 30 keV would be helpful since the previous measurements are quite old (>17 years). Improved measurements above about 50 eV would be valuable in determining the gross structure in alpha. Measurements are planned at ORNL from thermal to 30 keV.

## II. STATUS FOR ALPHA OF $^{235}$U

A. Resolved Resonance Region. Smith and Young[5] carried out an analysis of total and partial cross sections below 82 eV for ENDF/B-III; this parameter set was retained for ENDF/B-V. Uncertainties in normalization of up to 12.5% have been indicated[6] in part of the basic data in the lower resolved resonance region. Status was discussed in detail by Keyworth and Moore.[7]

B. Unresolved Resonance Region. For ENDF/B-V, energy scale adjustments were made by Bhat to reconcile differences in fission data sets of Lemley et al.,[8] Perez et al.,[9] and Gwin et al.,[10] and absorption data of Perez et al. and Gwin et al. Alpha was obtained from averages of the energy adjusted sets, from 82 eV to 25 keV.

C. Fast Region. For ENDF/B-V, alpha above 25 keV is unchanged from Version IV. New data by Beer and Käppeler[11] between 10 and 500 keV show good agreement with that of de Saussure et al.,[12] but have somewhat different shape compared to Gwin et al.[10] and Weston et al.[13] lying systematically higher at energies above 100 keV, although in agreement within the uncertainties of 8% to 10%.

## CONCLUSIONS AND RECOMMENDATIONS FOR $^{235}$U.

Alpha for $^{235}$U has been measured by a number of experimenters in the neutron energy range of concern with an average uncertainty of about 8%. There is a need for higher accuracy measurements, particularly in the resonance region. If additional measurements are undertaken, great care should be exercised to understand systematic uncertainties and a realistic error file should be obtained. Any additional measurement should be documented such that an average uncertainty of less than 8% can be fully justified.

## III. STATUS FOR ALPHA OF $^{239}$Pu.

A. Resolved Resonance Region. Alpha in the resolved resonance region for ENDF/B-IV was calculated from the parameter set obtained by Smith, Garber, and Kinsey (unpublished). This region for ENDF/B-V was unchanged from Version IV. The Ribon evaluation[14] summarizes the current status in this range.

B. Unresolved Resonance Region. The primary data source for ENDF/B-V was that of Gwin et al.[15,16] with the fine structure carried over from ENDF/B-IV. Reference 16 contains data on alpha for $^{239}$Pu obtained by Weston and Todd which has not been published elsewhere. Measurements of alpha for $^{239}$Pu were reviewed and evaluated by Kononov and Poletaev.[17]

C. Fast Region. For ENDF/B-V the evaluation of ENDF/B-IV was adopted. This evaluation was based upon the data of Gwin et al.,[15,16] Lottin et al.,[18] and Hopkins et al.[3] More recent reviews are by Kononov and Poletaev,[17] Gwin et al.[15] and Rjabov et al.[19]

## CONCLUSIONS AND RECOMMENDATIONS FOR $^{239}$Pu.

Alpha for $^{239}$Pu in the neutron energy range from 0.5 eV to 500 keV has been measured with an average uncertainty of about 8%. There is some evidence shown in Reference 16 that an accuracy of better than 8% can be achieved with present techniques. There is a need for accurate measurements if they are carried out with careful attention to systematic errors and a realistic error file is obtained. Any such new measurement should be fully documented.

## IV. STATUS FOR ALPHA OF $^{241}$Pu.

There is only one extensive measurement of alpha for $^{241}$Pu from thermal neutron energies to 250 keV by Weston and Todd.[20] The uncertainty in these measurements is about 9%.

## CONCLUSIONS AND RECOMMENDATIONS FOR $^{241}$Pu

Since $^{241}$Pu is important for Pu fueled reactors it is very desirable to have more than one differential measurement of alpha on which to base the evaluations of this quantity. This is a difficult measurement, however, a corroborative measurement is needed.

## SUMMARY

For $^{235}$U and $^{239}$Pu the value of alpha from 0.5 eV to 500 keV is known with an average uncertainty of about 8%. Additional precision measurements are needed if careful attention is given to systematic errors, a realistic error file is obtained, and the measurements are fully documented.

For $^{233}$U additional measurements are needed, particularly in the neutron energy range above 100 eV. Measurements are planned at ORNL.

There is only one extensive differential measurement of alpha for $^{241}$Pu. A corroborative experiment would be worthwhile.

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# $^{238}$U(n,$\gamma$) Cross Section Below 100 keV and $^{238}$U Resonance Parameters

G. de Saussure

June 29, 1979

## DESCRIPTION

The $^{238}$U capture cross section and resonance parameters are of major importance for the calculation of performance parameters of thermal and fast reactors, such as the effective multiplication constants, the breeding ratio as well as the Doppler coefficient of reactivity.

In most recent evaluations the $^{238}$U cross sections are represented by resolved resonance parameters up to about 4 keV and by unresolved (statistical) parameters above 4 keV, up to 45 keV in ENDF/B-IV and up to 149 keV in ENDF/B-V.

The resolved resonance parameters are obtained by a consistent analysis of transmission, self-indication, capture, and scattering high-resolution measurements in conjunction with theoretical models of statistical properties and whatever other information may be available on the properties of specific resonances.

The unresolved parameters in ENDF/B versions IV and V were generated by using "conventional values" for the average s-wave parameters and adjusting the average p-wave neutron width to "fit" evaluated average capture and inelastic-scattering cross-sections. In this procedure the average p-wave neutron widths are redefined every few hundred eV.

## STATUS

### I. Resolved Range (below 4 keV)

A large number of important new measurements of the low energy $^{238}$U cross sections have been reported in the past five years, and some older measurements have been carefully reexamined. Much of this work was stimulated by the apparent inability of ENDF/B-IV, and other evaluations, to predict the $^{238}$U capture rate in thermal critical lattices. The problem was extensively discussed at a "Seminar on $^{238}$U Resonance Capture" held in Brookhaven National Laboratory on March 18-20, 1975.[1]

The recent measurements and reanalyses of older data are discussed in "Evaluation of the $^{238}$U Neutron Cross Sections for Incident Neutron Energies up to 4 keV,"[2] a paper describing the ENDF/B-V evaluation of the $^{238}$U cross sections below 4 keV, where detailed references to the measurements are given. The most significant changes suggested by the recent work is a reduction by about 15% of the capture widths of the first three s-wave levels and an increase of from 10 to 20% of the strength function above 1.5 keV. These changes have reduced but not completely eliminated the discrepancy between the computed and measured $^{238}$U capture rates in thermal critical lattices.[3]

### II. Unresolved Range (4 to 100 keV)

Recent measurements of the $^{238}$U(n,$\gamma$) cross section above a few keV are discussed by Poenitz et al.[4] in "Evaluated Fast Neutron Cross Sections of Uranium-238," a document describing in particular the ENDF/B-V evaluation of the infinitely dilute $^{238}$U capture cross section above 20 keV. The capture cross section measurements have generally large uncertainties (of the order of 6%), and show significant discrepancies even among the most recent data. In the range 20 to 100 keV the new data suggest a higher $^{238}$U(n,$\gamma$) cross section than ENDF/B-IV, and indeed ENDF/B-V is higher, by amounts ranging from a fraction of 1% to 10%. On the other hand the analysis of integral benchmark experiments suggests[5] lower group cross sections than obtained with ENDF/B-IV.

## CONCLUSION AND RECOMMENDATIONS

### I. Resolved Range (below 4 keV)

Very recent transmission measurements performed at Harwell[6] have yielded resonance parameters up to 520 eV in substantial agreement with the ENDF/B-V evaluation. Further work will include an investigation of the systematic errors and possibly an extension of the analysis to higher energy regions.

As previously stated, even with ENDF/B-V the discrepancy between the computed and measured $^{238}$U capture rates in thermal critical lattices is not completely eliminated. This suggests additional experimental and evaluation work; however, it is perhaps not completely clear, at present, that the discrepancy implies inadequacy of the $^{238}$U resolved resonance parameters.

### II. Unresolved Range (4 to 100 keV)

The large differences between the various measurements of the $^{238}$U(n,$\gamma$) cross section in the unresolved region are very unfortunate, in view of the importance of the data to the nuclear energy programs. However, the large uncertainties in the measurements and the discrepancies result from the inherent difficulties of capture measurements in the 1 to 100 keV range. The difficulties result in part from the low value of the $^{238}$U binding energy, and also from the necessity to perform important background, efficiency, and multiple scattering corrections to the raw data. Additional measurements of the $^{238}$U(n,$\gamma$) cross section should probably attempt to reduce the uncertainties associated with these corrections by stressing new approaches and better techniques.

Perhaps an even more important problem, particularly below 10 or 20 keV, is to test the validity of the representation of the unresolved resonance parameters. The technique used in ENDF/B-IV and V is straightforward from a "mechanical" viewpoint, but it is not unique and there is very little experimental confirmation of the adequacy of the model. Sowerby[7] and others[8] have recently discussed the problems associated with finding adequate unresolved parameters for $^{238}$U. Recent experiments at Harwell[9] and at the University of Missouri[10] are designed to test the use of unresolved parameters to predict resonance self-shielding and Doppler effect. Probably the most efficient method to improve the $^{238}$U cross section description would consist of extending the resolved range representation to energies above 4 keV. New measurements of the $^{238}$U(n,$\gamma$) cross section below 10 keV are planned at ORNL. It is hoped that the result of these measurements combined with recent transmission measurements[11,12] will allow such an extension of the resolved region.

The importance of improving the representation of the $^{238}$U cross sections in the keV region is confirmed by a large number of recent studies of fast reactors,[13] thermal reactors,[14] and Doppler effect.[15]

## TABLES

In Table I is a comparison of infinitely dilute and strongly self-shielded ($\sigma_0$ = 10 b) group cross sections computed with ENDF/B versions IV and V. The comparison is over a somewhat arbitrary 8 group structure covering the resolved range. The values were obtained by R. Q. Wright, at ORNL, using MAT 1262 and 398, respectively. The two last columns of the table indicate that the differences between version IV and version V are typically a few percent for either unshielded or shielded group constants. However, it is important to note that the changes in the shielded group constants are not proportional to the changes in the dilute group constants (the signs are not even the same in most cases). This indicates that an overprediction of the $^{238}$U capture in strongly self-shielded critical lattices does not necessarily imply that the evaluated infinitely dilute capture cross section is too high.

TABLE I. Comparison of ENDF/B-IV and V $^{238}U(n,\gamma)$ Group Cross Sections Over the Resolved Energy Range

| Group | EL, EH<br>eV | Dilute $^{(1)}$<br>IV<br>b | <br>V<br>b | Shielded $^{(2)}$<br>IV<br>b | <br>V<br>b | $\frac{V - IV}{IV}$<br>Dilute<br>% | <br>Shielded<br>% |
|---|---|---|---|---|---|---|---|
| 1 | .4 - 100 | 45.55 | 45.65 | 1.700 | 1.636 | +0.22 | -3.8 |
| 2 | 100 - 170 | 23.80 | 22.91 | 1.220 | 1.235 | -3.7 | +1.2 |
| 3 | 170 - 280 | 11.46 | 10.96 | .8472 | .8867 | -4.4 | +4.7 |
| 4 | 280 - 450 | 3.578 | 3.489 | .6686 | .6754 | -2.5 | +1.0 |
| 5 | 450 - 750 | 3.538 | 3.521 | .7720 | .8120 | -0.48 | +5.2 |
| 6 | 750 - 1230 | 2.692 | 2.777 | .8167 | .8066 | +3.2 | -1.2 |
| 7 | 1230 - 2040 | 1.753 | 1.774 | .7037 | .6889 | +1.2 | -2.1 |
| 8 | 2040 - 3360 | 1.352 | 1.401 | .7541 | .7874 | +3.6 | +4.4 |

(1) $$\frac{\int_{EL}^{EH} \sigma_{n\gamma} \frac{dE}{E}}{\int_{EL}^{EH} \frac{dE}{E}}$$

(2) $$\frac{\int_{EL}^{EH} \frac{\sigma_{n\gamma}}{\sigma_t + \sigma_o} \frac{dE}{E}}{\int_{EL}^{EH} \frac{1}{\sigma_t + \sigma_o} \frac{dE}{E}}$$ ($\sigma_o$ = 10 b)

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15. S. K. Bhattacharyya, "Measurement of the Doppler Reactivity Worth of $UO_2$ and $ThO_2$ in an LMFBR Spectrum," TANSAO 32, 1-832 (1979) p. 784.

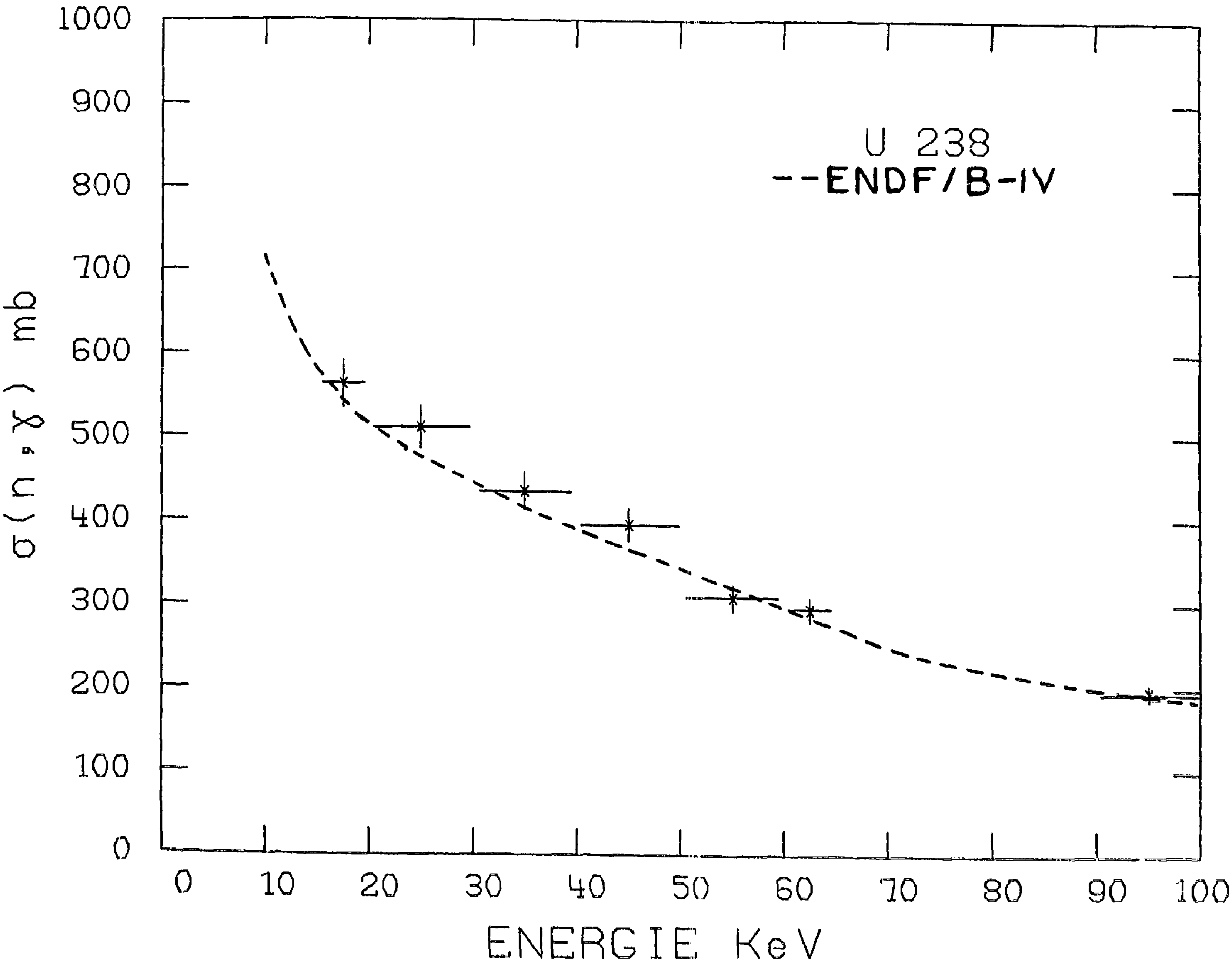
# FIGURE

The figure shows a comparison between the recent data of Le Rigoleur et al. and ENDF/B-IV. The figure is from the reference:

> CEA-R-4788 - Le Rigoleur Claude - ARNAUD André - Taste Jean
> Absolute Measurements of Neutron Radiative Capture Cross Sections for $^{23}$Na, Cr, $^{55}$Mn, Fe, Ni, $^{103}$Rh, Ta, $^{197}$Au, $^{238}$U in the keV Energy Range.

This reference also contains a detailed discussion of the experimental uncertainties of the measurements.

Other data are compared to ENDF/B-V in the report quoted in ref. 5.


U 238
--ENDF/B-IV
σ(n,γ) mb
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
ENERGIE KeV

# $\bar{\nu}_p(E)$

J.R. Smith

July 16, 1979

## Description

$\bar{\nu}_p(E)$ is the average number of prompt neutrons per fission, expressed as a function of energy. The data are important for calculation of reactor properties, particularly for fast reactors. The 1979 compilation of requests for Nuclear Data, BNL-NCS-51005, lists request for $\bar{\nu}_p(E)$ data with accuracies of 1% for $^{235}U$ and 0.3% for $^{239}Pu$, in the energy region thermal to 3 MeV.

## Status

There is an abundance of both experimental and evaluative work on this subject. Tsukada and Fuketa(1) provide a list of recent measurements and evaluations, summarize the problems, and present a review of the many evaluations. The present comments should be viewed as addenda to that more lengthy discussion.

Differences of 1% to 2% persist amongst the various measurements in the region of interest. There is disagreement over the question of whether the scatter in the data represent real structure in the $\bar{\nu}_p(E)$ energy dependence or merely random data scatter. A further cloud has been cast over the whole picture by Gwin's new $^{235}U$ data,(2) and the suggestion it carries that $\bar{\nu}_p$ ratio measurements may be subject to a systematic error associated with foil thickness. A finite foil thickness, together with a finite discriminator bias on the fission chamber, preferentially eliminate from the experiment those fission events in which the fission fragment path lies close to the plane of the foil. The corresponding fission neutrons are emitted preferentially in the direction of the fragment. The result is that a portion of the most sensitive volume of the scintillator is incorrectly charged with the task of detecting neutrons for which no histories have been started.

The foil thickness effect is itself part of the discrepancy, because experimenters do not agree on its magnitude. It is certainly a function of the geometry of the experiment and of the electronics used. The data of Condé(3) are cited as indicating that foil thickness effects are negligible for foils 1 mg/cm$^2$ and thinner. This could be both a misinterpretation and a misapplication of the Condé data.

The problems outlined here are common to all $\bar{\nu}_p$ ratio measurements. A particular problem is posed by $\bar{\nu}_p(E)$ for $^{233}U$, which appears to fall below its thermal value before beginning the familiar rise with energy. It is difficult to envision this apparent behavior as being truly physical.

## Conclusions and Recommendations

The $\bar{\nu}_p(E)$ data do not yet fulfill the requested accuracy requirements, and it is not clear that such accuracies are attainable with available techniques. All experimenters should reexamine their experiments to be sure that sample thickness effects are properly taken into consideration for their specific experimental configurations. More cooperative sessions should be held like that of Boldeman, Fréhaut, and Walsh,(4) to iron out differences in the performance and interpretation of experiments.

## References

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# ENERGY PER FISSION

W.H. Walker

November 1979

## Description

Reactor power and energy per fission are closely related. It is important, therefore, to know energy per fission accurately, to understand the cause of any uncertainty in its value, and to have a clear widely-accepted definition.

In this status review the symbols and definitions of ENDF/B-V (Garber et al, 1978) will be used, namely, that the total energy released per fission, ET, comprises the kinetic (or photon) energy of all the fragments and radiations emitted by the fission process, both prompt and delayed. The delayed emissions are summed over an infinite period.

The part of ET that appears as heat in a reactor is given by

$$\begin{aligned} EH &= ET - EINC - ENU \\ &= QG - ENU \\ &= ER - EINC \end{aligned}$$

where QG is the energy increase per fission by incident neutrons with average kinetic energy EINC and ENU is the kinetic energy of anti-neutrinos emitted in fission product $\beta$-decay.

Heating due to capture of the $\bar{\nu}-1$ excess neutrons, a reactor-core dependent quantity, is not included in EH.

## Status

QG can be obtained by mass balance (Walker, 1968) or by summing component energies. James (1969), Unik and Gindler (1971) and Sher and Beck (1979) have compared the mass balance value for U-235 with the measured component energies and obtained a best set of data by least squares methods. Other data are also included in some of these evaluations, such as ratios of fission fragment kinetic energies for different fissile nuclides.

The major uncertainty in EH is expected to be introduced by ENU. The delayed components of ET, due to fission product decay, are EB (beta), EGD (delayed gammas), END (delayed neutrons) and ENU. All four components can be calculated from detailed fission product files such as ENDF/B-IV, and EB, EGD, EB+EGD and END can also be measured.

In their analysis Sher and Beck (1979) have given much greater weights to decay components calculated from ENDF/B-IV than to measured values. This is because measurements show considerable discrepancies, and are mostly limited to thermal fission of U-235, whereas the ENDF/B-IV data provide a consistent set for a wide range of fissile nuclides and incident energies.

However, Walker (1979) recently compared $\beta,\gamma$ and calorimetric (EB+EGD) measurements for U-235 thermal fission and concluded that the calculated values are too low. Extrapolating to the anti-neutrino component indicates that the ENDF/B-IV based values are 1-3 MeV too low, depending on the average number of decays per fission.

In ENDF/B-IV only values of ER are listed. These appear as the Q-values in file 3, MT=18(fission). They are compared below with the results of Sher and Beck (1979).

| Fissioning Nuclide | Th-232 | U-233 | U-234 | U-235 | U-236 | U-238 | Pu-238 |
|---|---|---|---|---|---|---|---|
| Q-value [a] | 184.4 | 190.3 | 193.0 | 192.5 | 193.0 | 194.0 | 200.0 |
| QG-ENU [b] | 185.1 | 191.3 | 189.7* | 194.1 | 192.1 | 195.1 | 197.4* |

| Fissioning Nuclide | Pu-239 | Pu-240 | Pu-241 | Pu-242 | Am-241 | Am-243 | Cm-244 |
|---|---|---|---|---|---|---|---|
| Q-value [a] | 198.6 | 195.0 | 200.5 | 200.0 | 200.0 | 200.0 | 200.0 |
| QG-ENU [b] | 200.1 | 197.2* | 202.1 | 199.3* | 202.1* | 201.2* | 203.2* |

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[a] From ENDF/B-IV

[b] From Sher and Beck(1979). * indicates value based on systematics only.

Since the Sher and Beck values are expected to be too high because of weight given to calculated fission product components, values smaller than theirs by 1-3 MeV should be approximately correct ($\sim$1 MeV for U-233 and Pu-239 to $\sim$3 MeV for Th-232 and U-238). Thus the ENDF/B-IV Q-values are reasonably accurate, with 1 or 2 exceptions, on the basis of our present knowledge.

Note that the energy components listed in ENDF/B-V are taken from an unpublished preliminary report (Sher et al 1976) and differ somewhat from those of Sher and Beck (1979). Both are based on the fission product yields, decay data and neutron emission probabilities of ENDF/B-IV. Thus energy per fission values and their components in ENDF/B-V will not be consistent with the fission product and $\bar{\nu}$ data. Although ET is not expected to change significantly, there may be appreciable changes in the delayed components.

The evaluations by Sher et al include only 16 of the 24 nuclides for which components are listed in ENDF/B-V. For 6 of the 10 cases in which EINC$\neq$0 the evaluators have set ET equal to QG instead of QG+EINC (U-234, U-236, Np-237, Pu-238, Pu-242, Am-243). In addition, in order to keep ET equal to the sum of components EFR values have been reduced by an amount equal to EINC.

## Conclusions

Anyone using the mod 0 energy components for the 6 fissile nuclides listed above should refer to Sher et al (1976) for appropriate EINC values, and add them to the corresponding values of ET and EFR listed in ENDF/B-V. These corrections should be incorporated in mod. 1.

Until the ENDF/B-V fission product file becomes available for testing against experimental results the values of Sher and Beck (1979) provide the most extensive, up-to-date set of total energy per fission, ET, and its components. However, if the delayed components are too small, as suspected, then, since ET is accurately known, the prompt components will be too large.

Additional measurements are required of $\beta$,$\gamma$ and total decay power, both to reduce the uncertainty in the contribution at short decay times and to resolve differences between the separate $\beta$ and $\gamma$ components, EB and EGD, and calorimetric values ECAL. According to Walker (1979) ECAL/(EB+EBD)$\gtrsim$1.15 over the time range 1000 s to $10^5$ s for U-235 thermal fission.

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# STATUS OF THE ENERGY-DEPENDENT PROMPT FISSION NEUTRON SPECTRA

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August 29, 1979

## REACTION

.Energy Dependent Prompt Fission Neutron Spectra.

## DESCRIPTION

The prompt fission neutron energy spectrum must be provided for all fissile and fertile materials that are included in the design of a fission or fusion-fission hybrid reactor (or critical assembly) and that are born within the system during its operating lifetime. This spectrum parameter is also important in understanding differential and integral parameter measurements in operating reactors and in calculational mockups. In addition, weapons effects studies rely upon information pertinent to the fission neutron energy spectrum of different materials. The importance of the dependence of the prompt neutron fission spectrum upon incident neutron energy has not been established at this time although data testing results of reaction rates where high thresholds are involved intimately depend upon the energy of the neutron which produces the fission. For the fission reactor, the important energy range is below 5 MeV but, for the fusion-fission hybrid, evaluated data are required to at least 15 MeV.

## STATUS*

### A. Experimental

The status of the experimental data vary widely depending upon the isotopes studied. The general trend, however, is that most of the measurements available today have been made on U-235 and Pu-239 and are limited to the region below an incident neutron energy of one MeV, except for a few measurements on Th-232 and U-238 which have high-energy thresholds. Many measurements have been performed on the spontaneous fissioning isotope Cf-252. Due to its high flux for small

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*For the definitions of the terms used in this section and more specific information on usage, please refer to Appendix A.

sources and easy portability, Cf-252 is useful as a standard. Excellent review papers are abundant in number covering the data through about 1965. These are referenced and/or summarized in Ref. 1, the proceedings of the first IAEA meeting dedicated solely to a review of prompt fission neutron spectra. In 1975, the European-American Data Committee convened a specialists' meeting[2] during which the European experimentalists working in the field described their recent measurements. The most interesting results reported at this meeting indicated that the fission spectra for U-235 and Pu-239 were harder than previously accepted and that the Watt was a better representation of the spectra than the widely used Maxwellian distribution function.

The hardening of the spectra was due, in part, to the application of multiple scattering corrections in the target which had not been applied to the early measurements. Some recent experimental data not covered at the Harwell meeting can be found in Refs. 3, 4, and 5 on U-233, U-235, and the spontaneous fissioning of Cf-252, respectively. Finally, further experimental work on U-235 and U-238 was reported[6] recently which included an incident neutron energy of 7 MeV and where the emitted neutrons were recorded down to a few hundred keV.

One of the most difficult problems in measuring prompt fission spectra is that the detector must have a well known response function over a very wide energy range -- from a few hundred keV to approximately 15 MeV. Another difficulty lies in the differentiation between the fission neutron and the incident neutrons which are scattered by surrounding media (and support materials), both elastically and inelastically. For this reason, most measurements are made at very low incident neutron energies and the detector biased accordingly. If, however, one tries to obtain the shape and average energy of the neutron spectrum strictly from the "tail" of the distribution function, there are many pitfalls to overcome. The latest experiment by Frehaut et al.[6] was performed using coincidences between the fission fragments and the neutrons in order to separate several components of scattered neutrons recorded by the neutron detector from those emitted in the fission process.

A problem which is yet to be resolved is whether a low-energy component (below 1 MeV) exists in the fissioning of any isotope. That is, this component is reported as a peak below 1 MeV that cannot be reproduced by either the Watt or Maxwellian distribution functions. This peak is seen in some experiments but not others; in some experiments, it is observed in the raw data but then removed by performing the multiple-scattering corrections. None of the theoretical arguments commonly accepted today indicate such a phenomena should exist below the threshold for the (n,n'f) reaction.

Finally, experimental results are always reported as relative values and rarely cover identical ranges over which the outgoing neutrons were recorded. This makes comparisons between different data sets difficult to interpret since various methods for inter-normalizing the many sets are available to the user.

For a comprehensive discussion of these and other experimental problems, see the section contributed by J. C. Browne in Appendix A.

## B. Theoretical

Theoretical interest in predicting the (Z, A, and $E_0$) dependence of the prompt fission spectrum has been revived recently. See, for example, the contribution by J. R. Nix in Appendix A and the follow-on paper presented at the Atlanta American Nuclear Society Meeting.[7] Another theoretical paper was presented by Dietrich and Browne[8] at the Atlanta Meeting showing a comparison between experiments and a Hauser Feshbach prediction for Cf-252. Theoretical work is continuing with plans for incorporating $\bar{\nu}_p$ predictions as a function of energy into the formalism of Madland and Nix.

## C. Evaluated Spectra

All ENDF/B-IV evaluations for $\bar{\nu}_p$ spectra were represented by the Maxwellian distribution function except for U-233, which was a point-wise distribution that incorrectly included a delayed component. For U-235, U-238, Pu-239, and Pu-240, the effects of second- and third-chance fission were included as an inelastic or (n,2n) component using an evaporation type spectrum.

For Version V, the energy-dependent Watt formalism was introduced (see Appendix A and Ref. 9). In agreement with the recommendations from the Harwell Specialist's Meeting, the spectra were changed to a Watt distribution for the important fissile and fertile materials with a larger average energy. A few comparisons at the lowest incident energy in the files are listed below.

| | VERSION IV | | VERSION V | |
|---|---|---|---|---|
| | Formalism | $\bar{E}_n$ (MeV) | Formalism | $\bar{E}_n$ (MeV) |
| Th-232 | Max | 1.8857 | Watt | 2.133 |
| U-233 | 3-Segment | - - | Watt | 2.073 |
| U-235 | Max | 1.985 | Watt | 2.0308 |
| U-238 | Max | 1.9377 | Watt | 1.9817 |
| Pu-239 | Max | 2.085 | Watt | 2.112 |
| Pu-240 | Max | 2.019 | Max | 2.019 |
| Pu-241 | Max | 2.0395 | Max | 2.03955 |
| Pu-242 | Max | 2.00961 | Max | 2.0055 |

$\bar{E}_n$ is the average energy of all neutrons associated with the fission process, Max is the Maxwellian formalism, and the Watt is represented by the energy dependent parameters as described in Appendix A.

The ENDF/B-V files are discussed in Ref. 9. The first few Versions of ENDF/B for U-235 relied heavily on the earlier work of Rosen, Cranberg, and Barnard, as shown in Fig. 1. An equally good fit to these data could be obtained with the Watt two-parameter formalism. For Version IV, the average energy for U-235 was increased from 1.935 (Fig. 1) to 1.985 MeV. It is interesting to note that a different choice for normalization may have produced somewhat better agreement between the Rosen and Barnard results at both high and low energies. More importantly, perhaps, is a comparison of the shapes of the Watt and Maxwellian formalism. Figure 2 shows the ENDF/B-V data for U-235 (Watt) compared to a Maxwellian and the Madland and Nix formalism[7] using the same average energies. Note that the Maxwellian has ∿7% more neutrons at 100 keV than the Watt and ∿5% more than the theoretical model.

Finally, the ENDF/B-V evaluation for U-235 is plotted in Fig. 3 for 7-MeV incident neutrons, ∿1.6 MeV above the second-chance fission threshold (see Ref. 9). Note that the average energy of all neutrons associated with the fission process is shifted from 2.142 MeV (for the fission of n + U-235) to 1.993 MeV, after the spectra of the (n,n'f) neutrons are taken into account.

## CONCLUSIONS AND RECOMMENDATIONS

There is no on-going experimental program in the U.S. or European communities that is dedicated to improving our knowledge of the energy dependence of the prompt neutron fission spectrum. The theoretical work underway may help determine which measurements would be most useful in predicting the spectrum as a function of Z, A, and $E_0$. While it is necessary to gain a better understanding of the physics for evaluation purposes, the importance of the change in shape and average energy with incident energy is not well determined.

For thermal and fast reactor applications, the shape and average energy of the prompt spectrum has been shown to be important. The desired accuracy and reproducibility of the data on U-235, U-238, Pu-239, and U-233 have not yet been reached. Data on Th-232, Pu-240, Pu-241, and Pu-242 are in very poor shape and a new evaluation is needed for the spontaneous fission of Cf-252. The spectrum for the spontaneous fission of Cf-252 has not yet been added to the ENDF/B-V files.

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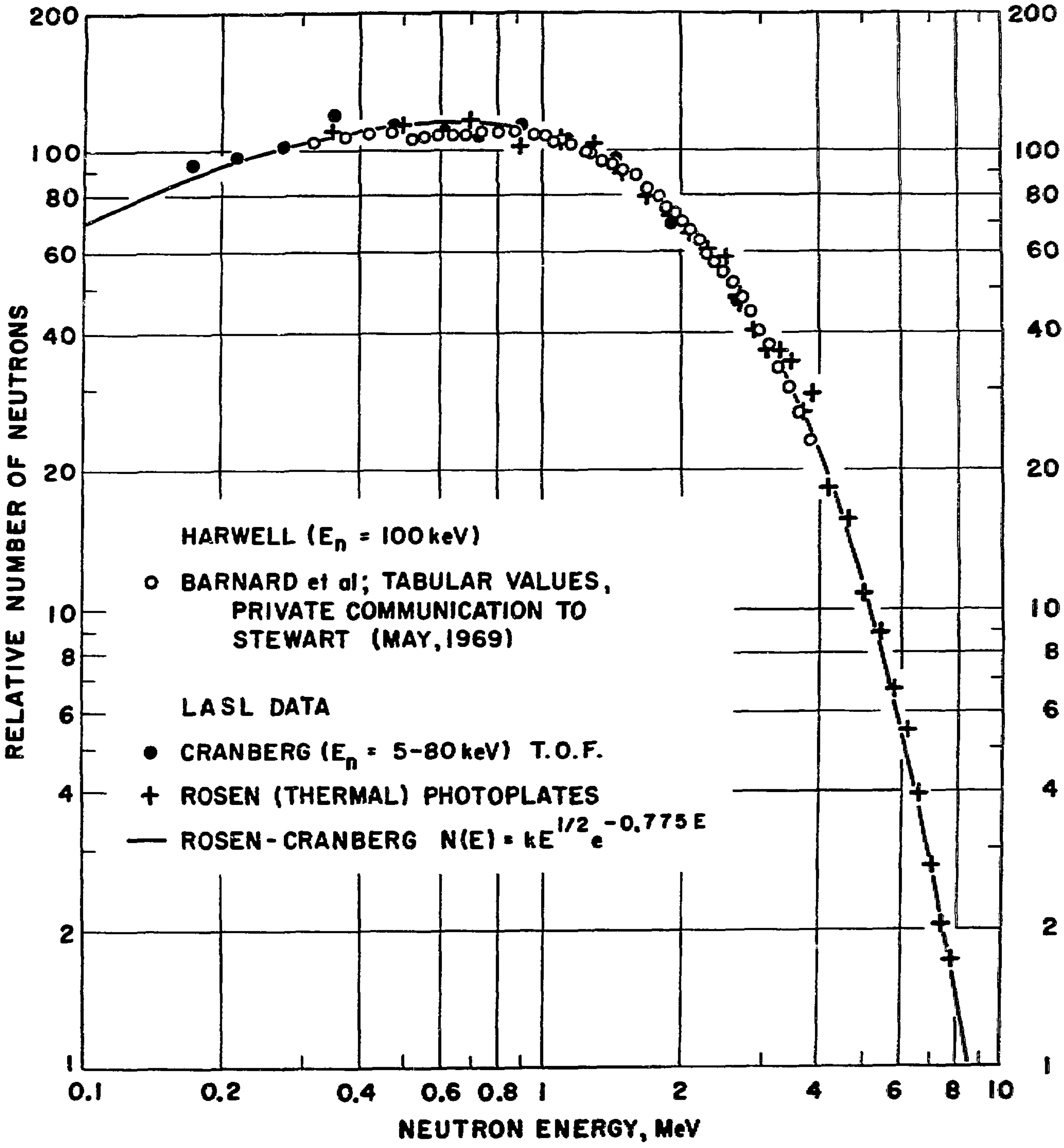

Fig. 1.
Neutron spectrum from neutron-induced fission of U-235.

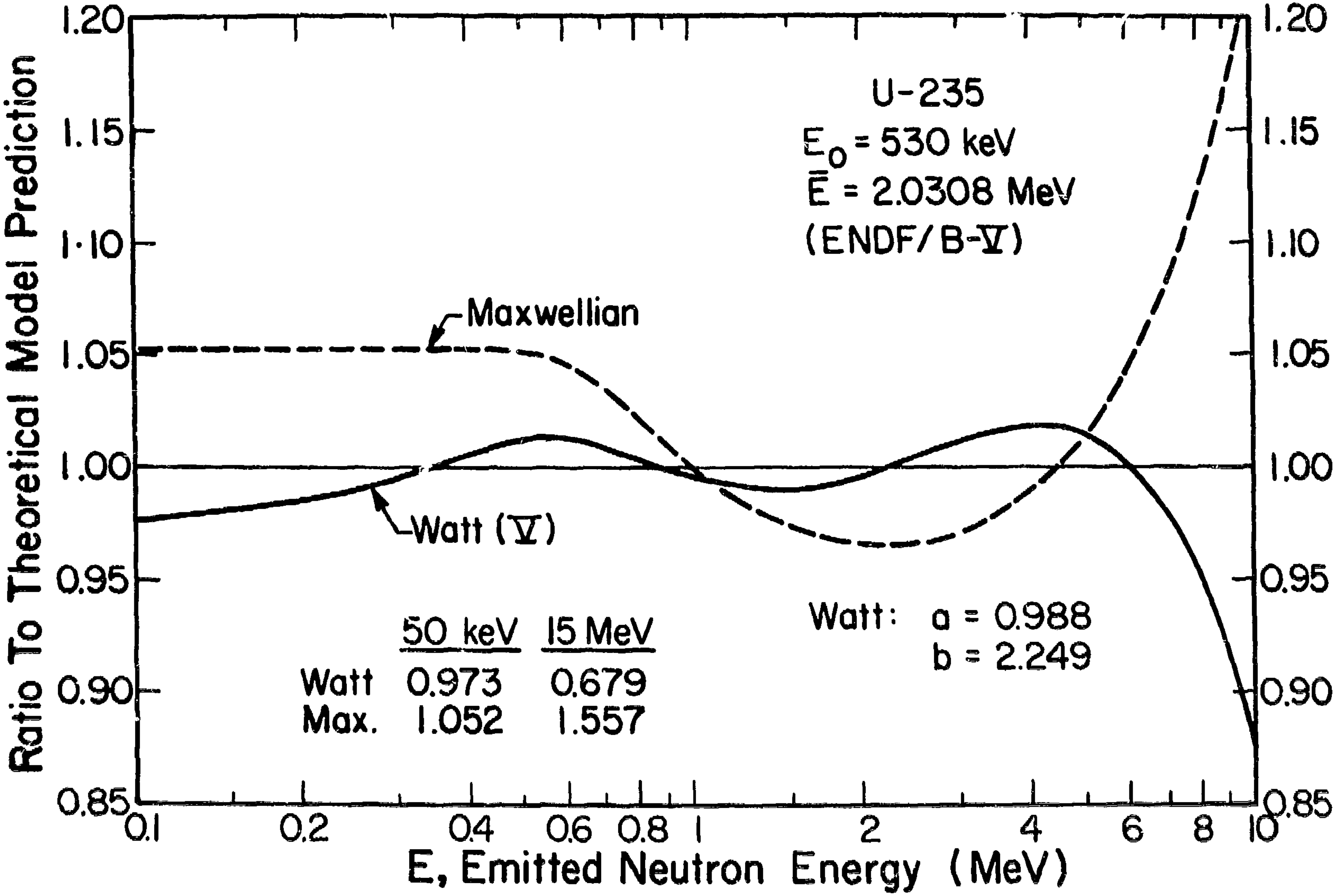

Fig. 2.
Calculated prompt neutron fission spectra for U-235 using different models.

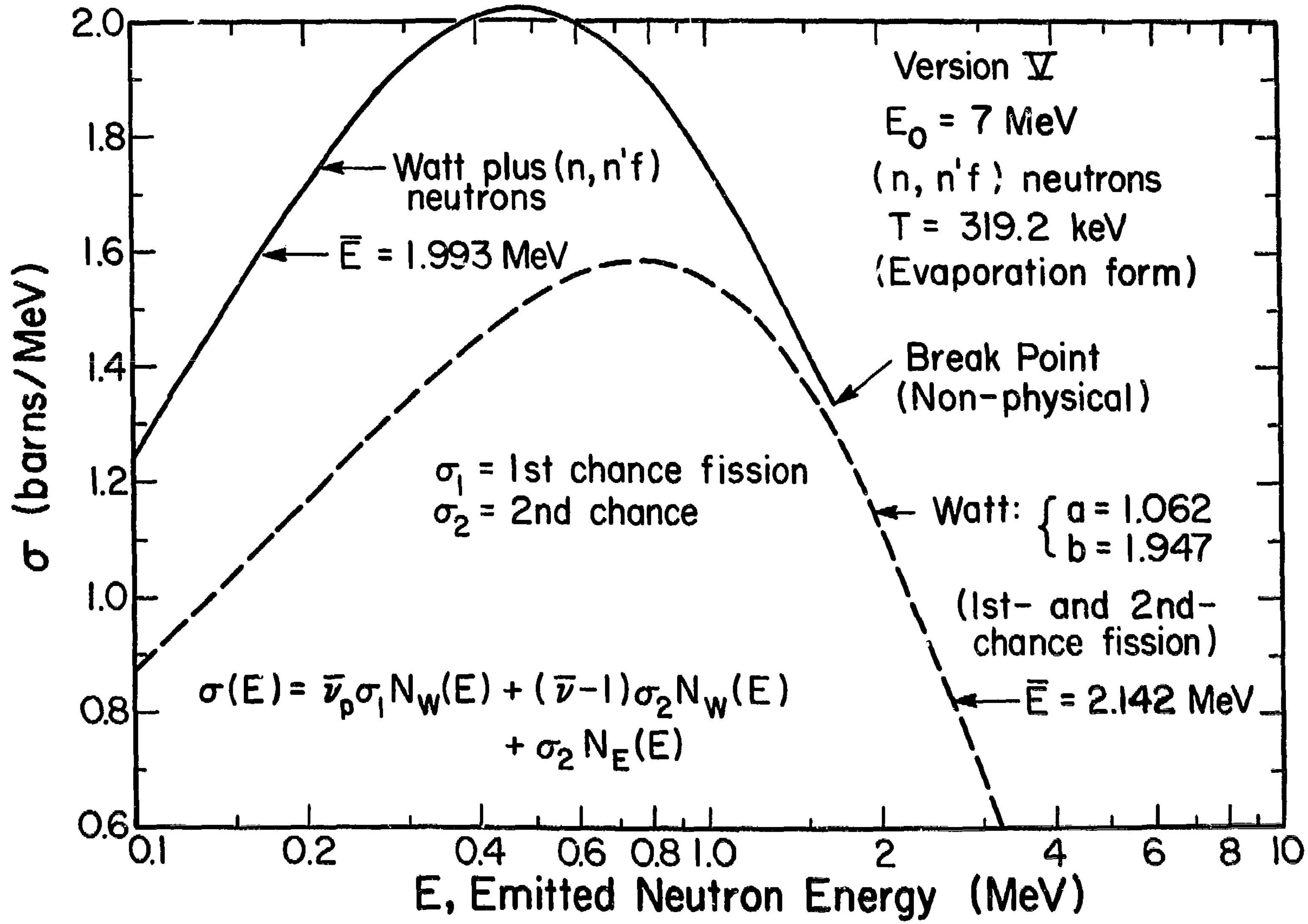

Fig. 3.
U-235 prompt neutron fission spectra.

APPENDIX A

# Summary of Fission Spectrum Workshop

## held at the National Neutron Cross Section Center

## Brookhaven National Laboratory

## October 23, 1978

**Leona Stewart, Chairman**

## ATTENDEES

J. C. Browne, Lawrence Livermore Laboratory
M. Bhat, Brookhaven National Laboratory
C. Eisenhauer, National Bureau of Standards
J. Hardy, Jr., Bettis Atomic Power Laboratory
B. R. Leonard, Jr., Batteile Northwest
D. Mathews, General Atomic, San Diego
J. R. Nix, Los Alamos Scientific Laboratory
D. Olsen, Oak Ridge National Laboratory
S. Pearlstein, Brookhaven National Laboratory
R. W. Peelle, Oak Ridge National Laboratory
E. Pennington, Argonne National Laboratory
W. P. Poenitz, Argonne National Laboratory
J. R. Smith, EG&G, Idaho Falls
P. G. Young, Los Alamos Scientific Laboratory

# *SUMMARY OF FISSION SPECTRUM WORKSHOP*
held at the National Neutron Cross Section Center
Brookhaven National Laboratory
October 23, 1978

by

Leona Stewart
Chairman

## ABSTRACT

In response to an action by the Standards Subcommittee of the Cross Section Evaluation Working Group, a workshop was convened to determine the status of available information on prompt fission neutron spectra. The experimental data were reviewed and theoretical models were developed. The current ENDF/B fission neutron spectra files were summarized. Further work is currently under way, especially to provide a better theoretical tool to represent energy-dependent fission spectra.

## I. INTRODUCTION

This workshop covered a full day with much audience participation. It would be impossible to provide a complete summary and, in fact, the outline here does not include many items from my notes since the subjects are to be covered in invited papers planned for the Reactor Physics Division Special Session on Prompt Fission Neutron Spectra at the Atlanta ANS Meeting (June 3-8, 1979). In fact, most of the information presented at our Workshop will be covered at the Atlanta ANS Meeting.

## II. FISSION SPECTRUM WORKSHOP

### A. General (Leona Stewart)

The impetus for this meeting was to establish the status of fission neutron spectra, both prompt and delayed, and the energy-dependent delayed yields based on the needs of the evaluators of fissile and fertile materials. Due to time limitations and the fact that few of the people present were cognizant of the status pertaining to delayed neutron yields and spectra, only the prompt spectra were discussed at this particular workshop. Neither the prompt nor delayed gammas associated with the fission process were included on the agenda, although the $\gamma$ yields and spectra are also important in the evaluation process.

The needs of the evaluators were summarized and the point stressed that almost nothing is known about the dependence of the prompt fission spectra upon incident neutron energy since energy-dependent experimental measurements available today are sparse and the few data sets which exist are inconclusive. That the shape and average energy of the fission neutron spectrum is important has been ably demonstrated for several thermal reactor systems by Steen[1] and Hardy et al.[2] at Bettis. Some work has also been undertaken on fast-reactor systems.[3] Both the shape and average energy are important in predicting reaction-rate ratios in fast-reactor benchmarks, especially for reactions dominated by threshold effects.

The Evaluated Nuclear Data File, Version B (ENDF/B) has provision for several types of spectral information. For the prompt neutron fission spectra, Version V has been updated to allow an energy-dependent Watt formalism and this form is recommended for the important fissile and fertile isotopes: Th-232, U-233, U-235, U-238, and Pu-239. Although the Watt formalism can be used for all Version V evaluations, most of the fissile and fertile species will have the simpler Maxwellian form carried over from Version IV. These two expressions are given below.

1. Energy-dependent Maxwellian

$$F(E_{n'}) = C(E_0)\sqrt{E_{n'}}\ e^{-E_{n'}/T(E_0)}\ ; \quad \bar{E}_{n'} = 3T/2 \quad ,$$

where C is the normalization constant, and T is the so-called temperature of the distribution function, at the incident neutron energy $E_0$.

2. Energy-dependent Watt formalism

$$F(E_{n'}) = D(E_0)\ e^{-E_{n'}/a(E_0)}\ \sinh\sqrt{b(E_0)E_{n'}}\ ; \quad \bar{E}_{n'} = 3a/2 + ba^2/4 \quad ,$$

where D is the normalization constant.

Strictly speaking, other formats for fission neutron energy spectra are allowed in ENDF/B. In fact, above the first-, second-, and third-chance fission thresholds, a combination of two or more spectra are required. As an example of the representation of the spectrum associated with second-chance fission, (n,n'f), the first neutron is generally assumed to be evaporated from the compound nucleus X, leaving the target nucleus Y at an excitation energy high enough to fission. Therefore, the prompt spectrum <u>associated</u> with the second-chance fission process consists of the combination of the inelastically scattered neutron from the target Y and the neutron spectrum from the fissioning of the target nucleus Y. To this spectrum must be added the contribution from first-chance fission through the compound nucleus.

To properly represent the fission process, the evaluator must provide the total fission cross section as a function of incident neutron energy in ENDF File 3, MT=18, where MT is the reaction index. The total fission cross section is the sum of all partial fission cross sections such as (n,n'f) (MT=20), (n,2nf) (MT=21), (n,3nf), etc., along with the direct fission of the compound nucleus usually represented as (n,f) (MT=19). The average number of prompt $(\bar{\nu}_p)$ and delayed $(\bar{\nu}_d)$ neutrons per fission along with their sum are placed in File 1 in retrievable form. Since few neutrons appear in a fission reactor spectrum above the second-chance fission threshold, thermal and fast-reactor calculations can usually be simplified to the treatment of first-chance fission alone.

## B. Theoretical (Ray Nix)

Ray Nix introduced a theoretical derivation representing the prompt fission spectra. The derivation, based on physical grounds, was reduced to a Watt distribution upon the application of several simplyfing assumptions.* He pointed out that the Watt formalism is a better representation of the prompt spectra than the Maxwellian function used for most ENDF materials. However, the Watt parameters chosen for ENDF/B-V were based on fits to data rather than physics constants; therefore, a better understanding of the physical derivation is most important.

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* These assumptions are currently being tested and further developments will be presented at the forthcoming Atlanta ANS Meeting.

Briefly, Nix derived spectral parameters by starting with the Weisskopf formalism for the evaporation of neutrons in the center-of-mass system for a highly excited nucleus at a single temperature T.

$$\phi(\varepsilon) = k_0\, \sigma(\varepsilon)\, \varepsilon\, e^{-\varepsilon/T} \quad ,$$

where $\varepsilon$ is the emitted neutron energy, k is the normalization constant, and $\sigma(\varepsilon)$ is the compound nucleus cross section for the inverse process and is assumed to be independent of energy. The probability p(T), corresponding to the distribution of fission-fragment excitation energy, is approximated by a linear function of T from T = 0 to the upper limit $T_{max}$.

The spectrum $\Phi(\varepsilon)$ obtained by integrating over T is given in terms of an exponential integral, which is approximated by the functional form

$$\Phi(\varepsilon) = k_1 \sqrt{\varepsilon}\, e^{-\varepsilon/T_{ef}} \quad .$$

The average energy $\bar{\varepsilon}$ corresponding to the original and approximate forms for $\Phi(\varepsilon)$ is

$$\bar{\varepsilon} = \frac{4}{3} T_{max} = \frac{3}{2} T_{ef} \quad ,$$

which leads to the relationship

$$T_{ef} = \frac{8}{9} T_{max} \quad .$$

Transformation into the laboratory system reduces to the Watt distribution

$$N(E) = k_2\, e^{-E/T_{ef}} \sinh\left( 2\sqrt{EE_F} \,/\, T_{ef}\right) \quad ,$$

where E is the emitted neutron energy in the laboratory system and $E_F$ is the average fission-fragment kinetic energy per nucleon. The two constants $E_F$ and $T_{ef}$ need not be adjusted to reproduce prompt fission neutron spectra, but can instead be determined a priori from other physical considerations.

(The derivation will be given in detail in a forthcoming paper by Nix and Madland; to be published. In addition, the assumptions used in the derivations themselves will be studied to show the magnitude effects.)

For a fixed (Z,A), it is reasonable to make the further assumption that $E_F$ is constant with increasing neutron energy; that is, the extra energy goes into excitation energy. Then using the thermal measurements to determine $T_{ef}$, one approximates the energy dependence of $T_{ef}$ by

$$T_{ef} \approx T^0_{ef} + \frac{4}{9}\frac{E_n}{aT^0_{ef}} ,$$

where $a \approx A/8$ MeV.

As mentioned earlier, the Watt formalism has been used for several ENDF/B-V materials but no physical interpretations were taken into account in deriving the two constants $T_{ef}$ and $E_F$. Therefore, further work is under way to check the validity of the approximations for the Watt derivation and also to check the changes which could be incorporated into ENDF/B-VI to give physical significance to the parameters.

## C. Experimental

1. Review of Available Data (John Browne). The experimental problems of measuring prompt fission spectra were outlined in detail by John Browne. Everyone agreed that experiments are difficult to perform and, in fact, very few measurements exist which satisfy minimum criteria. The following problems were outlined by Browne with others contributing from the floor:

a. Was $(n,\gamma)$ discrimination used? If so, was it properly taken into account?

b. Was the detector efficiency measured? If so, how and exactly what data were used as the Standard? As an example, was the (n,p) assumed isotropic in the efficiency measurement? Were relativistic corrections applied? If the detector efficiency was calculated but not measured, then how well could the calculated efficiency be determined?

c. How was the energy scale determined? Very little information, if any, is given in most reports. Even though the energy scale was accurately determined, resolution effects inherently lead to a biased shape for N(E) especially at high energies where the statistics are poor and the resolution effects large. Bo Leonard suggested these effects can be as high as 10-20% if no attempt is made to correct for resolution.

d. The energy scales are determined differently for TOF using a spontaneous fission source and that for a neutron-induced fission event. Questions have arisen regarding shape corrections which should be applied for Cf-252. (Whether this problem has been resolved was not known at the time of the meeting).

e. Angular distribution effects of the neutrons emitted from neutron-induced fission have not been studied in enough detail. Since the fission-fragments, themselves, are very anisotropic, depending upon (Z,A) and incident neutron energy and most of the neutrons are emitted from the moving fragments, angular distribution effects may be important at some energies.

f. For the experiments John Browne reviewed, he found that the sample thicknesses used varied greatly yet the data reduction analysis was not always performed in a consistent way. The samples were sometimes solid cylinders and other times hollow cylinders.

g. Whether or not air scattering, multiple scattering in the target, and other corrections were properly made is not always clear.

h. The dependence of the prompt neutron spectrum upon incident neutron energy is not well determined experimentally, even below the 2nd-chance fission threshold. Above this threshold, the spectrum is expected to have three components but this has not been determined experimentally.

i. The energy range covered by the measurements also varies greatly; for example, neutrons from 1-5 MeV may be detected in one experiment and from 0.5 to 15 MeV in another. These data are always relative and difficult to compare directly without some choice of normalization between the two. Even more important, different runs of the same experiment often disagree, and/or give results well outside the errors assigned to the average values.

j. The methods used for obtaining the average energy of the fission spectrum neutrons are not always equivalent yet often the analytic parameters and average energies are the only data published. If the data cover a wide enough range, the average energy should be checked by simple numerical integration of the results as measured.

Browne also discussed briefly Hauser-Feshbach calculations[4] which he had described in a paper published several years ago. He presented a summary outlining problems he found in recent experimental papers on fission spectra. The group completely endorsed the idea that experimentalists should include brief comments in their write-ups to insure that their data could be employed in a consistent manner.

2. Fission Spectrum Effects in $\bar{\nu}$ Measurements (J. Richard Smith). The effect of the fission spectrum upon $\bar{\nu}$ measurements is concerned principally with neutron leakage in the experiment involved. In manganese bath measurements the

neutron loss through leakage is usually near 0.25% for a fission spectrum. Differences in spectrum shape have some effect on this figure, but in view of the small size of the correction, small changes in the shape of the assumed spectrum are of relatively minor importance.

Spectral shape has a greater effect in liquid scintillators whose efficiency for fission spectrum neutrons is near 85%. In these experiments a neutron efficiency as a function of neutron energy and angle of entry into the bath is established by observing the capture probability in the tank of neutrons which have been scattered by hydrogen in a recoil proton detector. The incident neutron energy is known either by time-of-flight or reaction kinematics so the energy and angle of the scattered neutron can be deduced from the pulse height in the proton recoil detector. As these efficiency measurements can cover only a limited portion of the scintillator's solid angle, Monte Carlo calculations, normalized to the measured efficiencies, are used to complete the picture. The efficiency relation thus determined must then be folded into the fission spectrum to determine the probability of observing an event in a $\bar{\nu}$ measurement. Boldeman modified his $^{252}$Cf $\bar{\nu}$ value by 0.1 to 0.2% when he received evidence that the average energy of the fission spectrum was higher than he had assumed. Frehaut has noted that changing to a Watt spectrum would change his $\bar{\nu}$ values by 0.21%. These are sizeable changes for a quantity for which better than 0.5% accuracy is desired.

## D. Energy Dependence of the Prompt Spectra

For the time being, theoretical treatment will be further pursued and checks made against the few experiments which exist. The general consensus is that we have a long road ahead before we can place confidence in our data on energy-dependent spectra.

## E. Status of Delayed Yields and Spectra

This item was put off until a later date since the people apprised of the problem did not attend this special session.

## F. NBS Standard Spectra (Charles Eisenhauer)

Eisenhauer has developed "Standard" spectra for U-235 at thermal and for spontaneous fission of Cf-252. These spectra are represented by a segmented formalism. That is, the spectra have been split into energy intervals based on activation measurements and then each segment expanded analytically in powers of E. The result is essentially a correction to a Maxwellian distribution. It was noted, however, that the "corrected" Maxwellian for U-235 is very close to the Watt distribution except for a large number of neutrons below 1 MeV often but not always seen in recent measurements. Eisenhauer has under way a new analysis for both U-235 (thermal only) and for Cf-252 and close coordination with CSEWG will be maintained in any reanalysis of the NBS standards. The large proportion of neutrons below 1 MeV has surfaced in many experiments and must be considered by all users and evaluators, not restricted to NBS standards applications.

## G. Adjourned

The meeting was adjourned with the recommendation that experimental and theoretical work should continue with the hope that the ENDF/B-VI files could be improved. In addition, better physical understanding of the fission process would be very useful in the evaluation procedures.

## ACKNOWLEDGMENTS

The participation and contributions of those attending the workshop are gratefully appreciated.

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# Half-Life of $^{239}$Pu

A.D. Carlson

October 1979

## Description

The half-life of $^{239}$Pu is required for many nuclear applications such as inventory measurements for safeguarding nuclear processing plants and assaying samples for neutron cross section measurements.

## Status

There has been much concern over an apparent systematic difference of about 300 years between calorimetric and alpha-particle counting techniques(1) for measuring this half-life. Vaninbroukx has examined the $^{239}$Pu half-life measurements in detail in the 1975 and 1977 NEANDC status reports (CBNM/RN/11/75 and ANL/ND-77-1). He noted that the recent (mostly preliminary) measurements are converging on the lower value of ~ 24100 years. Since that time the measurements of Jaffe(2) have been published. He used both alpha particle counting and mass spectrometric methods to obtain a value of 24131 ± 16 years.

The latest half-life value for $^{239}$Pu recommended by the Nuclear Data project(3) is 24110 ± 100.

The U. S. Department of Energy's Half-Life Evaluation Committee has recently completed its work(4) on $^{239}$Pu. This represents a thorough investigation of this half-life employing calorimetric, alpha-particle counting, and mass spectrometry techniques using well characterized samples. The results do not support the existence of technique dependent unidentified systematic errors. The final value obtained was 24119 ± 26 years. The participating laboratories in this investigation are the Los Alamos Scientific Laboratory, the Lawrence Livermore Laboratory, the Argonne National Laboratory, the Monsanto Research Corporation's Mound Laboratory, Rockwell International's Rocky Flats Plant and the National Bureau of Standards.

## Conclusions and Recommendations

The latest measurements of the $^{239}$Pu half-life appear to be consistent and independent of method. The accuracy of the determination is ~ 0.1% which should be satisfactory for sample assay for neutron cross section measurements. It is recommended that the value determined by the half-life committee, 24119 ± 26 years, be selected as the present best value of the $^{239}$Pu half-life.

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# $^{240}$Pu Half-life

by

Norman E. Holden

May 11, 1979

## I. DESCRIPTION

The half-life of $^{240}$Pu is required for assaying plutonium samples by alpha activity for neutron cross-section measurements, and for plutonium accountability procedures.

## II. STATUS

There has been considerable variation in the published values of the $^{240}$Pu half-life, where alpha counting provided the higher values and mass spectrometry and calorimetry provided the lower values. This situation is similar to the $^{239}$Pu half-life measurement case. The most recent determination was made by the Argonne group(1) and the results were intermediate between the previous values (see Table I). The half-life value in the Evaluated Nuclear Structure Data File(2), 6537±10 years, predates the most recent experimental value.

## III. CONCLUSIONS and RECOMMENDATIONS

The result of Jaffey et al.(1), is the most accurate half-life determination to date and is recommended.

Table

Table I $^{240}$Pu Half-Life

| Author | Year | Half-life (Years) |
|---|---|---|
| Inghram (3) | 1951 | 6505±45 |
| Butler (4) | 1956 | 6600±100 |
| Dokuchaev (5) | 1959 | 6610±55 |
| Oetting (6) | 1967 | 6533±10 |
| Jaffey (1) | 1978 | 6569±6 |

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# $^{241}$Pu Half-life

by

Norman E. Holden

May 11, 1979

## I. DESCRIPTION

The half-life of $^{241}$Pu is important for neutron cross-section determinations, fuel mangement, and safeguards.

## II. STATUS

There has been a discrepancy of 7-8 percent among the reported half-life values of $^{241}$Pu in the literature (see Table I), where some early measurements were revised using later data on the $^{241}$Am half-life. Determinations are in progress at Harwell, GEEL, and NBS at the present time. Table II lists the results of these most recent measurements. There has been a three fold decrease in the spread of the results, but an approximate 2 percent uncertainty still exists.

## III. CONCLUSIONS and RECOMMENDATIONS

From the results of Table II, the best estimate of the $^{241}$Pu half-life would be $14.4 \pm 0.1$ years at this time. Because of the significant difference between the mass spectrometric results and the $^{241}$Am ingrowth determinations, further work on this half-life is still justified.

Tables

## Table I - Early Measurements of $^{241}$Pu Half-Life

| Author | Year | Method | Half-Life (years) |
|---|---|---|---|
| Thompson (1) | 1950 | $^{241}$Am growth | 15.4 |
| MacKenzie (2) | 1953 | " | 14.1±0.2 |
| Rose (3) | 1956 | " | 13.9±0.3 |
| Brown (4) | 1960 | " | 14.14±0.26 |
| Smith (5) | 1961 | " | 14.2±0.3 |
| Whitehead (6) | 1972 | " | 14.98±0.15 |
| Stephan (7) | 1966 | Reactivity | 13.63±0.36 |
| Shields (8) | 1970 | Mass Spec | 14.6±0.4 |
| Cabell (9) | 1968 | Mass Spec | 14.98±0.33 |
| Nisle (10) | 1970 | Reactivity | 14.63±0.27 |
| Cabell (11) | 1971 | Mass Spec | 15.10±0.14 |
| Carden (12) | 1970 | Mass Spec | 14.64 |
| Zeigler (13) | 1973 | Mass Spec | 14.89±0.11 |
| Jordan (14) | 1974 | Calorimetry | 14.355±0.007 |
| Barnes (15) | 1975 | Mass Spec | 14.67±15.46 |
| Gunnick (16) | 1974 | Alpha counting | 14.5 |

## Table II - Recent Measurements of $^{241}$Pu Half-Life

| Author | Year | Method | Half-Life (years) |
|---|---|---|---|
| Lounsbury (17) | 1978 | Mass Spec | 14.25±0.10<br>14.31±0.10 |
| Crouch (18) | 1978 | Mass Spec | 14.24±0.12<br>14.53±0.12<br>14.53±0.08<br>14.33±0.21 |
| Whitehead (19) | 1978 | $^{241}$Am growth | 14.56±0.15 |
| Garner (20) | 1978 | Mass Spec | 14.38±0.07 |
| Vaninbroux (21) | 1978 | Mass Spec<br>$^{241}$Am ingrowth | 14.30±0.14<br>14.60±0.10 |

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# DELAYED FISSION NEUTRON SPECTRA

PLANNED TO BE INCLUDED AT A LATER DATE

# INELASTIC SCATTERING, FERTILE AND FISSILE NUCLEI.

PLANNED TO BE INCLUDED AT A LATER DATE.

# FAST NEUTRON CAPTURE: $^{232}$Th AND $^{238}$U

PLANNED TO BE INCLUDED AT A LATER DATE.

# FAST FISSION RATIOS

PLANNED TO BE INCLUDED AT A LATER DATE.

# HALF-LIVES OF U ISOTOPES

PLANNED TO BE INCLUDED AT A LATER DATE.

# SECTION C: OTHER NUCLEAR DATA

# Thermal Absorption Cross-Section for Natural Sulfur

J.R. Smith

July 1979

## Description

The thermal absorption cross section of sulfur represents a correction factor of about 4% in measurements of neutron source strength using the manganese bath. The 6% uncertainty quoted in BNL 325 leads to an uncertainty of nearly a quarter of a percent uncertainty in the derived neutron yields including $\bar{\nu}$ for $^{252}$Cf, measured by the manganese bath method.

## Status

The BNL 325 recommended value is 520 ± 30 mb, which is a weighted average of four reactivity measurements (1-4) whose values range from 490 to 545 mb. The error derived from the relative weights is about 15 mb, but in view of the small number of measurements and their range, the BNL error estimate is probably more nearly correct. There are two measurements (5,6) of sulfur total cross sections at low energies, whose analyses lead to thermal absorption cross section values of 620 and 590 mb, respectively. The latter values have traditionally been rejected out of hand, since they are subject to errors due to small angle and Bragg scattering in the sample, plus instrumental nonlinearities at low energies. However, the reactivity measurements themselves are subject to sample problems, since the sulfur absorption cross section is low, being half of the scattering cross section and considerably below the cross sections of materials used as standards. The reactivity measurements are nearly 30 years old and were part of general survey-type measurement programs. The sulfur measurements in particular did not receive the great care that might have been expected if the importance of the sulfur cross-section to the $\bar{\nu}$ problem had been realized. Any substantial movement of the value in the general direction of the results of the transmission measurements could be significant to the discrepancy.

## Conclusions and Recommendations

The problems can probably not be solved by evaluation alone. New measurements are required. These should employ high purity sulfur, moisture free, and accurately characterized for contaminant content and structure that could affect scattering. Measurements by at least two techniques should be made. An accuracy of 1% is needed, to reduce the sulfur contribution to the uncertainty in $\bar{\nu}$ to less than 0.05%.

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# $^{242}$Cm Resonance Capture Integral

by

Norman E. Holden

November 29, 1978

## I. DESCRIPTION

$^{242}$Cm is one of the transplutonium nuclides of interest in the actinide burnup chain and the resonance capture integral is needed to estimate the build-up of the higher actinides.

## II. STATUS

The only integral measurement is due to Schuman, who reported a value of 150±40 barns. Parameters have been calculated from the total cross section in the 1 to 265 eV energy range by Artamonov et al.,(2).

Using the parameters as measured by Artamonov, the resonance integral is 101 barns, with an additional contribution ≈10 barns from the $\frac{1}{v}$ component and 12 barns from the unresolved resonances above 265 eV using Dresner(3) and Itkin(4)

In the Schuman experiment, two samples of pure $^{241}$Am were irradiated in high flux ETR core positions. Resonance integrals were assumed for $^{241}$Am, $^{242}$Am and $^{242}$Cm and isotope ratios were calculated. Values giving the best fit were $^{241}$Am(n,$\gamma$) $^{242}$Am (16 hr) 850±60 barns, and $^{242}$Cm(n,$\gamma$) 150±40 barns.

The thicknesses of the cadmium shield were 3 mm, corresponding to a cadmium cutoff of 0.75 eV to 0.80 eV, and 7 mm, corresponding to a cutoff of ≈1 eV or larger. These cutoffs would eliminate contributions from the two major resonances at 0.308 eV and 0.576 eV and result in resonance integrals in the range measured rather than the 1224 barn value estimated previously(5) for the 16 hour $^{242}$Am production.

## III. CONCLUSIONS and RECOMMENDATIONS

Because of the thickness of the cadmium shields in the Schuman measurement, a value closer to the calculated resonance integral is recommended 130±20 barns, compared to the 156 barns value quoted in ENDF/B-V. A direct measurement of the

## III. CONCLUSIONS and RECOMMENDATIONS (cont.)

resonance integral would be useful, but it is not a critical need because of the general agreement between the differential and integral values.

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# $^{197}Au(n,\gamma)$ $^{198}Au$ Thermal Neutron Cross Section

by

Norman E. Holden

May 14, 1979

## I. DESCRIPTION

This cross section is the most common reference standard for capture reactions. It is used as a standard in the thermal neutron energy region and the resonance integral is also used as a standard.

## II. STATUS

This cross section has been reevaluated in the thermal region in preparation for the Fourth Edition of BNL-325(1). No thermal energy range measurements were considered which were made relative to another cross section. Measurements were only considered for which high resolution and accuracy in the wavelength determination were obtained. This eliminated problems with an epithermal component and the shape and temperature of the neutron flux. The resonance integral is based on the one absolute measurement for which sufficient details are available and the value calculated from resonance parameters.

## III. CONCLUSIONS and RECOMMENDATIONS

The cross section was measured below the Bragg scattering cutoff, where scattering contributions to the total cross section become small. The 1/V curve is fitted in this long wavelength region and extrapolated to a neutron velocity of 2200 meters per second. A correction for the non 1/V portion of the gold cross section due to the 4.9 eV resonance was made, using the Tellier(2) parameters for this resonance. The weighted average of the various experiments (see Table I), is 98.65±0.09 barns. The resonance integral is based on Jirlow's(3) measurement in the R1 reactor as corrected for the non-1/E shape by Johansson(4) and the calculation from resonance parameters using Tellier(2) with an unresolved component calculated using Dresner(5), Itkin(6). The recommended values are compared with ENDF/B-IV in Table II.

Tables

| Table I Quoted and Revised Results of Previous Measurements | | |
|---|---|---|
| Author | Quoted Value (barns) | Revised Value (barns) |
| Carter (7) | 98.7±0.6 | 98.72±0.45 |
| Egelstaff (8) | 98.6±0.9 | 98.6±0.9 |
| Gould (9) | 98.8±0.3 | 98.7±0.3 |
| Teutsch (10) | 98.9±0.3 | 98.8±0.3 |
| Als-Nielsen (11) | 98.6±0.2 | 98.58±0.22 |
| Dilg (12) | 98.68±0.12 | 98.63±0.11 |

| Table II Recommended Values Compared to ENDF/B | | |
|---|---|---|
| Evaluation | Thermal Cross Section (barns) | Resonance Integral (barns) |
| Holden (1) | 98.65±0.09 | 1550±28 |
| ENDF/B-IV | 98.8 | 1565 |
| ENDF/B-V | 98.71 | 1562 |

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# $^{59}Co(n,\gamma)$ $^{60m,60g}Co$ Thermal Neutron Cross Section

by

Norman E. Holden

May 15, 1979

## I. DESCRIPTION

The cross section is the most often used thermal neutron capture standard other than gold. It is often used as a resonance capture integral standard also.

## II. STATUS

This cross section has been reevaluated in the thermal energy range in preparation for the Fourth Edition of BNL-325. Because of the 10.5 minute isomer, which decays primarily to the ground state but has two weak beta branches, the activation cross section is .14% or 50 millibarns less than the absorption cross section. This factor was used to adjust all measurements to an absorption cross section basis. Of the twenty four measurements considered, only the five most precise and well documented values were used to determine the cross section. These five measurements are given in Table I. The five measurements of the activation cross section of the 10.5 minute isomer are shown in Table II.

The resonance integral must be determined from the integral measurements. The resonance parameters cannot be used because the capture width of the 0.132 eV resonance differs by 20% in the various measurements. Of the twelve integral measurements, three were not considered reliable because of insufficient data. The remaining nine values are given in Table III. Three measurements of the resonance integral for activation of the 10.5 minute isomer are given in Table IV.

## III. CONCLUSIONS and RECOMMENDATIONS

The weighted average of the thermal cross sections measurements in Table I is 37.18±0.06 barns and is recommended. The weighted average from Table II is 20.4±0.8 barns and is recommended for production of the 10.5 minute isomer.

The corresponding weighted averages from Tables III and IV for the resonance integral of $^{59}$Co and for production of the 10.5 minute isomer are 74.2±2.0 barns, and 39.2±1.8 barns, respectively and are recommended.

It might be noted that the inclusion of all 24 measurements of the thermal cross section leads to a weighted average of 37.20±0.08 barns (not recommended). In Table V, the recommended values are compared with ENDF/B.

Table I, $^{59}$Co(n,$\gamma$) Most Precise and Documented Thermal Capture Cross Section Measurements

| REFERENCE | REPORTED VALUE (barns) | RECOMMENDED VALUE (barns) |
|---|---|---|
| Vaninbroukx (1) | 37.4±0.3 | 37.3±0.3 |
| Merritt (2) | 37.09±0.27 | 37.16±0.27 |
| Kim (3) | 36.61±0.47 | 37.19±0.48 |
| Silk (4) | 37.245±0.11 | 37.245±0.11 |
| Dilg (5) | 37.145±0.07 | 37.145±0.07 |

weighted average (barns) = 37.178±0.056 (internal error)
0.036 (external error)

Table II, $^{59}$Co(n,$\gamma$) $^{60m}$Co 10.5 Minute Thermal Activation Cross Section

| REFERENCE | REPORTED VALUE (barns) | RECOMMENDED VALUE (barns) |
|---|---|---|
| Deutsch (6) | $\sigma^g/\sigma^m$ = 1.4±0.6 | 15.2±6.5 |
| Moss (7) | 18.3±1.7 | 21.8±2.0 |
| Keisch (8) | $\sigma^m/\sigma^g$ = 1.19± 0.16 | 21.8±1.4 |
| Schmidt-Ott (9) | 16.5 | 17.8±(2.0) |
| Gryntakis (10) | 18.80±.1.50 | 19.7±1.6 |

weighted average (barns) 20.4±0.84 (internal error)
0.84 (external error)

Table III $^{59}$Co Resonance Integral Measurements

| REFERENCE | REPORTED VALUE (barns) | RECOMMENDED VALUE (barns) |
|---|---|---|
| Johnston (11) | 74.8±5 | 75.2±5. |
| Feiner (12) | 81±4 | 74.8±7.2 |
| Eastwood (13) | 69.9±3.5 | 72.3±4.2 |
| Taylor (14) | | 73.3±7.9 |
| Le Sage (15) | 71.0±5 | 74.0±8.3 |
| Carre (16) | 68.7±5. | 70.4±7.0 |
| Kim (3) | 75.3±0.8 | 75.8±3.7 |
| Schuman (17) | 74.6±3 | 73.6±7 |
| Steinnes (18) | 77±4 | 76.2±8.1 |

weighted average (barns) 74.2±2.0 (internal error)

0.2 (external error)

Table IV Resonance Integral $^{59}Co(n,\gamma)$ $^{60m}$Co 10.5 Minute State

| REFERENCE | REPORTED VALUE (barns) | RECOMMENDED VALUE (barns) |
|---|---|---|
| Dahlberg (19) | | 39.2±3.5 |
| Eastwood (13) | | 38.4±2.3 |
| Gryntakis (20) | 39.7±4.3 | 42.7±4.6 |

weighted average (barns) 39.2±1.8 (internal error)

0.3 (external error)

Table V Comparison of Recommended Values with ENDF/B-IV

| EVALUATION | THERMAL CROSS SECTION (barns) | RESONANCE INTEGRAL (barns) |
|---|---|---|
| Present | 37.18±0.06 | 74±2 |
| ENDF/B-IV (21) | 37.2453 | 76.67 |
| ENDF/B-V | 37.23 | 73.78 |

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# $^{80}$Kr(n,$\gamma$) $^{81}$Kr Thermal Neutron Cross Section

by

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December 11, 1978

## I. DESCRIPTION

This cross section is used in tag gas studies. The thermal neutron energy region is of interest.

## II. STATUS

There have been no new significant experimental data on this reaction. A recent evaluation(1) examines the discrepancy in earlier experimental measurements and evaluations. Table I shows the results of earlier evaluations.

## III. CONCLUSIONS and RECOMMENDATIONS

Reassessments of the old measurements in the latest evaluation have resulted in a recommendation that the Bradley value(2) was the most reliable and the lack of details in earlier and later experiments did not allow one to place confidence in them. This evaluation is compared in Table II to the ENDF/B-IV value and is recommended for ENDF/B-V.

Tables

Table I - Results of Previous Evaluations

| Evaluation | Thermal Cross Section (barns) |
|---|---|
| Holden (3) | 11.5±0.6 |
| Walker (4) | 12.6 |
| Mughabghab (5) | 14.0±1.5 |
| ENDF/B-IV (6) | 14.3 |

Tables (cont.)

| Table II - Present Recommendation Compared to ENDF/B | |
|---|---|
| Evaluation | Thermal Cross Section (barns) |
| Holden (1) | 11.5±0.5 |
| ENDF/B-IV (6) | 14.3 |
| ENDF/B-V | 11.74 |

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# $^{136}$Xe(n,$\gamma$) $^{137}$Xe Thermal Neutron Cross Section

by

Norman E. Holden

September 28, 1978

## I. DESCRIPTION

This cross section is used in fission product studies. It is one component of the fission product rare gas of interest in reactor accident studies. The thermal neutron energy region and resonance integral over the resonance energy region are of interest.

## II. STATUS

There have been no new significant experimental data on this reaction. A recent evaluation(1) examined the discrepancy in earlier experimental measurements. The latest half life and gamma-ray-branching ratio data were used to correct the measurements, see Table I.

## III. CONCLUSIONS and RECOMMENDATIONS

As can be seen in Table I, the revision of these two experiments has essentially eliminated the previous discrepancy. Inserting the recommend thermal cross section into Bresesti's result(2) for the resonance integral gives a significantly larger value than ENDF/B-IV. The recommendations are compared to ENDF/B in Table II.

Tables

Table I - Quoted and Revised Results of Previous Measurements

| Author | Quoted Cross Section (mb) | Revised Cross Section (mb) |
|---|---|---|
| Bresesti (2) | 281 | 276 |
| Kondaiah (3) | 130 | 244 |

Tables (cont.)

Table II - Recommended Values Compared to ENDF/B

| Evaluation | Thermal Cross Section (barns) | Resonance Integral (barns) |
|---|---|---|
| Holden (1) | 0.26 | 0.74 |
| ENDF/B-IV (4) | 0.16 | 0.1238 |
| ENDF/B-V | 0.16 | 0.1238 |

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# $^{153}$Eu(n,$\gamma$) $^{154}$Eu Thermal Neutron Cross Section

by

Norman E. Holden

March 28, 1978

## I. DESCRIPTION

This cross section is used in fission product studies. The thermal neutron energy region and the resonance integral over the resonance energy range are of interest.

## II. STATUS

The measured values are shown in Table I. It is seen that the lowest value (Vertebny (1)) differs from the highest value (Sims (2)) by 50x the error reported on Sims measurement. The latest half life and non-unit g factor as well as other corrections result in the latest evaluation of these experiments as also shown in Table I.

## III. CONCLUSIONS and RECOMMENDATIONS

As can be seen in Table I, the revision of the various experimental values significantly reduces the previous discrepancies. The resonance integral is also revised by utilizing the latest cross section data, Table II . The recommended values are compared to ENDF/B-IV in Table III.

Tables

Table I - Thermal Cross Section Measurements

| Author | Quoted Value (barns) | Revised Value (barns) |
|---|---|---|
| Pattenden (3) | 448±16 | 286 |
| Tattersall (4) | 317±5 | 317 |
| Sims (2) | 639±7 | 319 |
| Vertebny (1) | 292±11 | 292 |
| Kim (5) | 603±23 | 309 |
| Widder (6) | 382±15 | 382 |
| Moxon (7) | 317±15 | 317 |

Tables (cont.)

Table II - Resonance Integral Measurements

| Author | Quoted Value (barns | Revised Value (barns) |
|---|---|---|
| Tattersall (4) | I' = 1280±100 | 1416 |
| Sims (2) | 3887±62 | 1885 |
| Scoville (8) | 1830±55 | 1830 |
| Van der Linden (9) | 1829±91 | 1181 |
| Kim (5) | 3414±197 | 1755 |

Table III - Recommended Values Compared to ENDF/B

| Evaluation | Thermal Cross Section (barns) | Resonance Integral (barns) |
|---|---|---|
| Holden (11) | 310±20 | 1610±250 |
| ENDF/B (10) | 453 | 1569 |
| ENDF/B-V | 299.9 | 1447.9 |

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