NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-35

Evaluated Nuclear Data File for ^{232}Th

by

J. Meadows, W. Poenitz, A. Smith, D. Smith, J. Whalen, and R. Howerton

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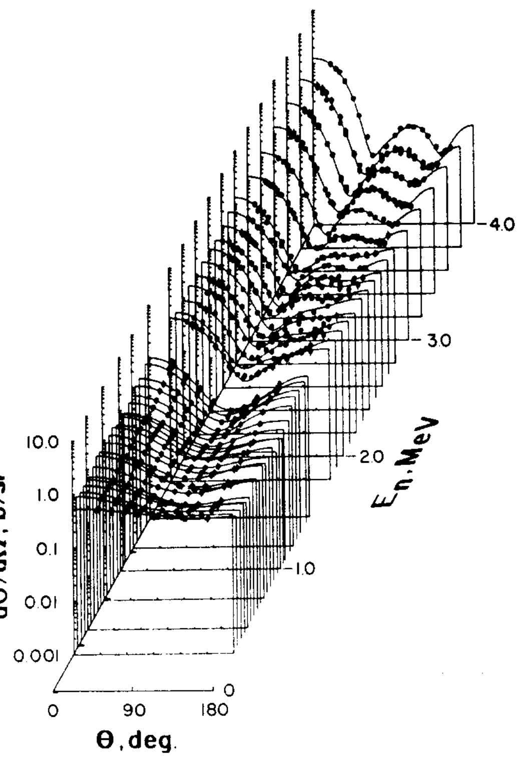

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NUCLEAR DATA AND MEASUREMENTS SERIES

The Nuclear Data and Measurements Series presents results of studies in the field of microscopic nuclear data. The primary objective is the dissemination of information in the comprehensive form required for nuclear technology applications. This Series is devoted to: a) measured microscopic nuclear parameters, b) experimental techniques and facilities employed in measurements, c) the analysis, correlation and interpretation of nuclear data, and d) the evaluation of nuclear data. Contributions to this Series are reviewed to assure technical competence and, unless otherwise stated, the contents can be formally referenced. This Series does not supplant formal journal publication but it does provide the more extensive information required for technological applications (e.g., tabulated numerical data) in a timely manner.

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EVALUATED NUCLEAR DATA FILE OF Th-232*

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September 1977

ABSTRACT

An evaluated nuclear data file for thorium is described. The file extends over the energy range 0.049 (i.e., the inelastic-scattering threshold) to 20.0 MeV and is formulated within the framework of the ENDF system. The input data base, the evaluation procedures and judgments, and ancillary experiments carried out in conjunction with the evaluation are outlined. The file includes: neutron total cross sections, neutron scattering processes, neutron radiative capture cross sections, fission cross sections, (n;2n) and (n;3n) processes, fission properties (e.g. nu-bar and delayed neutron emission) and photon production processes. Regions of uncertainty are pointed out particularly where new measured results would be of value. The file is extended to thermal energies using previously reported resonance evaluations thereby providing a complete file for neutronic calculations. Integral data tests indicated that the file was suitable for neutronic calculations in the MeV range.

*This work supported by the U. S. Department of Energy.

I. INTRODUCTION

The objectives of the present work were: 1) the provision of a contemporary fast-neutron-evaluated file for elemental thorium in the ENDF format (I-1), and 2) a comprehensive review of microscopic data for the interaction of fast neutrons with thorium resulting in guidelines for measurements which would make possible a subsequent and more definitive evaluation. The present file, together with an evaluation of the resonance region reported elsewhere (I-2), constitutes a contemporary evaluated file suitable for the assay of alternate nuclear-energy concepts involving thorium fuels in either a fission or fusion context. The evaluation is based upon data as available to October 1977. It was clear from the data review that the data base is uncertain in a number of areas and that future measurement programs must provide quantitative information before the present evaluation can be substantively improved. Where feasible, scoping measurements were implemented and completed in a time frame that permitted the resolution of some of the outstanding questions. The results of these measurements are outlined herein. Generally, these experimental results are a preamble to a more comprehensive set of experimental studies with the objective of greatly improved understanding of the interaction of fast neutrons with thorium.

The energy scope of this evaluation is 0.049 MeV (i.e. the threshold for inelastic neutron scattering) to 20.0 MeV. The reaction types include: neutron total cross sections (Sec. II), neutron scattering processes (Secs. III and IV), fission cross sections (Sec. V), neutron radiative capture cross sections (Sec. VI), (n;2n') and (n;3n') processes (Sec. VII) fission properties (e.g. prompt- and delayed-neutron emission) (Secs. VIII and IX), photon production processes (Sec. X) and data testing (Sec. XI). The subsequent sections outline the data base, evaluation procedures, judgments, and uncertainty guidelines for each of the above components.

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II. NEUTRON TOTAL CROSS SECTIONS

This portion of the evaluation was based upon experimental values from 0.025 to 15.0 MeV. The quality experimental data base was only fair with wide discrepancies between experimental values in some energy regions. With these discrepancies, considerable judgment, guided by consistency both within a data set and between sets, was required. Since all measured values were obtained using self-normalizing transmission techniques, renormalization of data sets was not justified. Therefore, data sets were accepted with subjective judgments as to their quality or were completely rejected. They were never adjusted. Regions of experimental uncertainty became evident early in the evaluation and new measurements were undertaken to assure reasonable validity of the evaluation. These new results, a part of the input data base, are outlined in a subsequent paragraph. There appears to be no experimental information above 15.0 MeV, thus the evaluation relied on theoretical extrapolation as indicated below.

In the energy range 0.049 to 1.0 MeV the evaluation relied primarily on the data of Refs. II-1 through II-5. These results are relatively consistent and of good accuracy and detail. Ref. II-6 was used above $\sim$0.8 MeV but not at lower energies due to the wide scatter of the cross section values. Ref. II-7 was assigned low weight due to the scatter of the data values. Refs. II-8 and -9 were considered above 0.5 MeV but rejected at lower energies where the results appeared anomalous. Ref. II-10 was completely rejected as the values were much lower than most of the other available information including results subsequently reported from the same laboratory. It was assumed that the total cross section followed a smooth energy dependence. At low energies this is probably an approximation as structure has been observed in the analogous ^{238}U cross section. The experimental results did not consistently define a similar structure in ^{232}Th and its omission from the evaluation will not impair most applied usage.

The evaluated file in the region 1.0 to 5.0 MeV is based primarily upon the experimental data of Refs. II-1, -2, -3, -6, -11, and -12. These data sets are relatively detailed and/or consistent. Refs. II-8 and -9 were considered with lesser weight. Their values are sparse and had small overall effect on the evaluation. Refs. II-13, -14, and -15 were rejected as being anomalous with respect to the main body of available information and/or relatively uncertain.

From 5.0 to 15.0 MeV the evaluation relied primarily upon the data of Refs. II-3, -11, and -16. Above 9.0 MeV only the data of Ref. II-11 was available excepting the single 14.0 MeV value of Ref. II-16 which agrees with the data of Ref. II-11. Refs. II-6 and -15 were not used in this region due to large uncertainties or results which appeared widely discrepant from the main body of the measured values.

Above 15.0 MeV the evaluation must rely on theoretical extrapolation to the 20.0 MeV upper limit. The theoretical extrapolation employed a coupled-channel model and the potential of Ref. II-17. This model and potential have been shown to be very suitable for ^{238}U, and can be reasonably applied to ^{232}Th as it is a very similar nucleus. Total cross sections of thorium were calculated at intervals of $\leq$1.0 MeV from 0.5 to 15.0 MeV. These calculated results agreed with the present experimentally-based evaluation over the entire energy range to within $\leq$4 percent. Moreover, calculations based on the same model were descriptive of elastic neutron scattering as outlined in Sec. III, below. Thus this model is a reasonable mechanism for extrapolation from 15.0 to 20.0 MeV.

The present evaluation is compared with that of ENDF/B-IV in Fig. II-1 (II-18). The two evaluations differ by as much as 15 percent in some energy ranges. These are large discrepancies and they will impact on other partial cross sections; e.g., inelastic scattering cross sections. The discrepancies between the two evaluations are often far larger than the estimated uncertainties associated with the present evaluation. The latter are outlined in Table II-1. These uncertainties reflect subjective judgments of the experimental data base and, above 15.0 MeV, of the model extrapolation.

As noted above, measurements were explicitly made to verify the experimental data base in regions of importance and uncertainty. These new experimental results were obtained using the techniques defined in Ref. II-19. The new values support the present evaluation over the measured energy range of 0.1 to 4.0 MeV as illustrated in Fig. II-2. The agreement is well within the respective uncertainties. These new experimental values are considerably different from values given in the ENDF/B-IV evaluation, particularly below 1.0 MeV.

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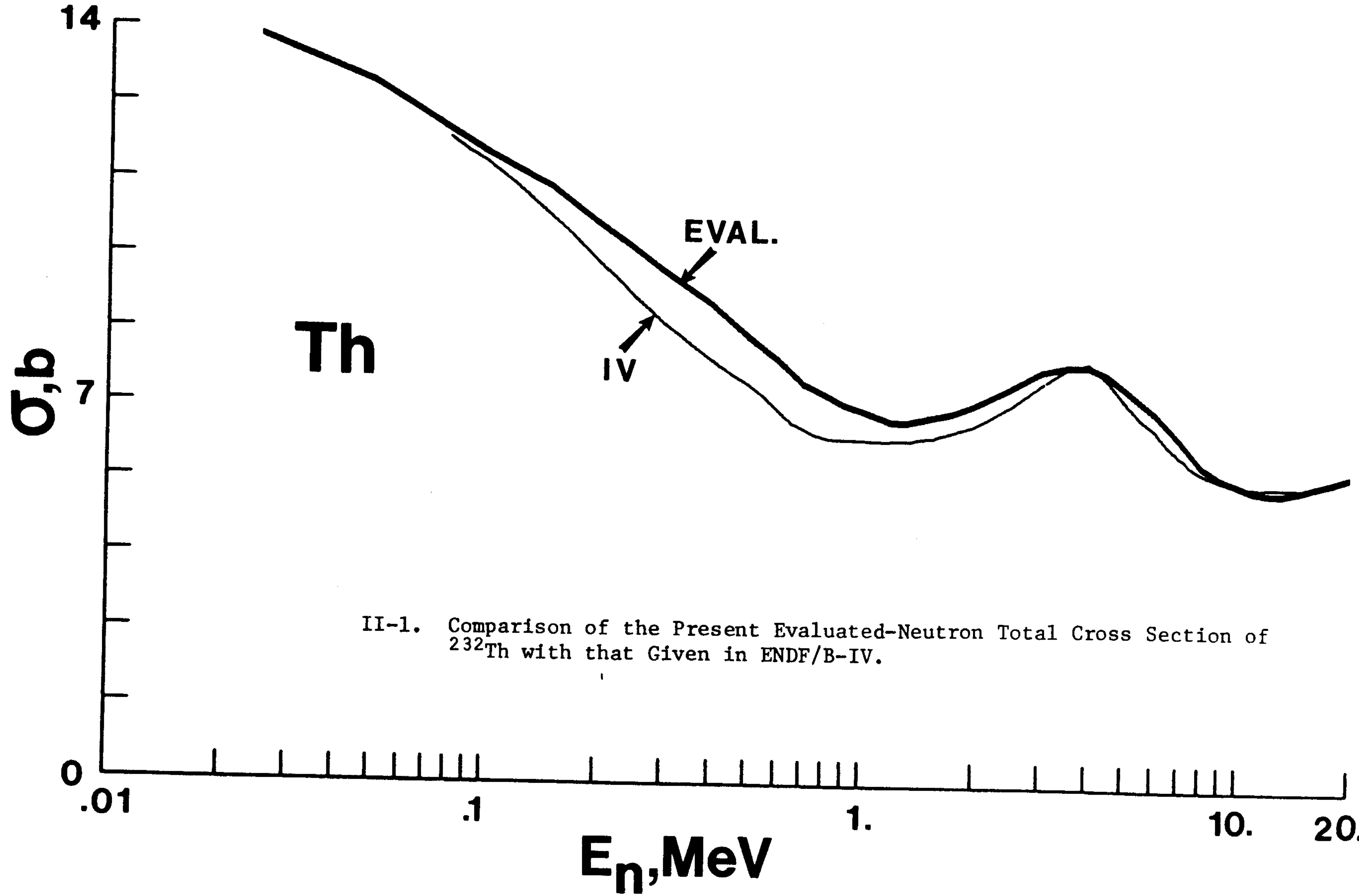
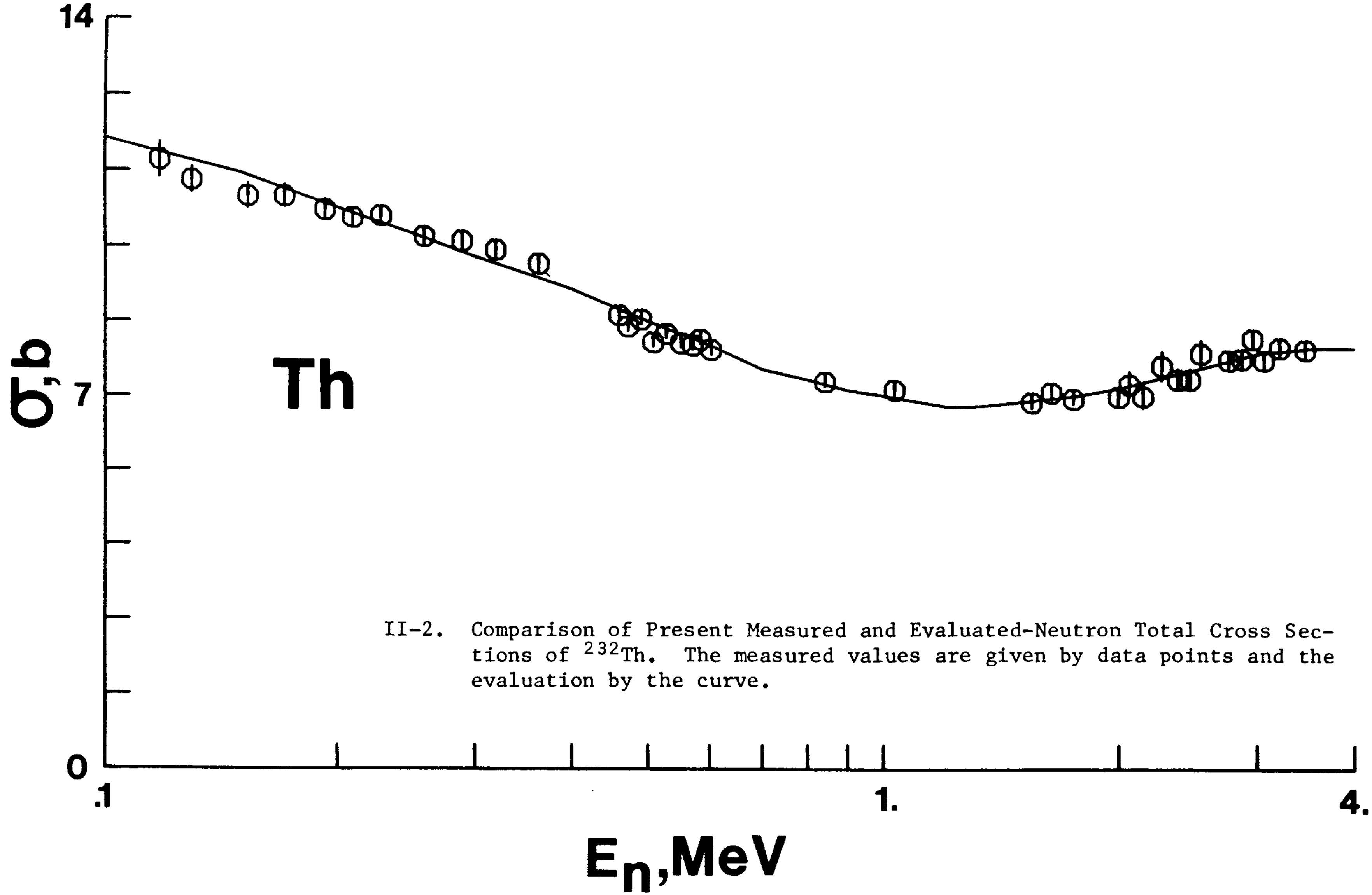
TABLE II-1. Estimated Uncertainties in the Present Evaluated Neutron-Total Cross Sections

E_n(MeV)	Uncertainties (%)
0.049	4.0
0.1	3.0
0.5	2.0
1.0	2.0
2.0	2.0
6.0	2.5
10.0	3.0
14.0	3.5
20.0	5.0



II-1. Comparison of the Present Evaluated-Neutron Total Cross Section of ^{232}Th with that Given in ENDF/B-IV.



II-2. Comparison of Present Measured and Evaluated-Neutron Total Cross Sections of ^{232}Th. The measured values are given by data points and the evaluation by the curve.

III. NEUTRON ELASTIC SCATTERING

The evaluation of this component was based upon available experimental information to $\simeq$2.5 MeV and the model of Ref. III-1 from 2.5 to 20 MeV. Below approximately 1.5 MeV the various nonelastic components were reasonably well defined and thus the elastic scattering magnitude was adjusted to assure consistency with the total cross section and the other partial cross sections. These adjustments were within the estimated uncertainties associated with the independent elastic scattering evaluation. Above 1.5 MeV the continuum inelastic scattering contribution was defined by the total cross section, the elastic scattering cross section and the remaining partial cross sections (e.g., fission, capture, (n;2n') and (n;3n')).

The experimental data base was very limited with only a few available results providing elastic-scattering cross sections free of inelastic-scattering contamination. At 49 keV the evaluation was based upon the total-scattering results of Langsdorf et al. (III-2). At this energy these values are equivalent to the elastic scattering cross sections and these particular measurements are believed reliable. From 0.5 to 1.5 MeV the evaluation relied upon the results of Smith et al. (III-3, -4, and -5). A number of these results were free of inelastic-scattering contributions. Where inelastic scattering was a contributing factor, corrections were made. In this energy range there were two additional distributions, one from Cox and Cox (III-6) and one from Walt and Barschall (III-7). Both included some contribution from the inelastic-scattering process. When corrected for inelastic scattering contributions, the results of Ref. III-6 appeared anomalous (low values). Similar corrections to the results of Ref. III-7 resulted in slightly too large values but there was some question as to the exact nature of the inelastic scattering contamination. Thus the results of Ref. III-6 and -7 were not used in the evaluation. From 1.5 to 2.5 MeV the only purely elastic-scattering results were from Smith et al. (III-5) and Haouat et al. (III-8). These were the key values in obtaining the evaluated elastic scattering cross sections in this energy region. Results obtained by Batchelor and Towle (III-9) at 2.0 MeV were not used in the evaluation since they contained appreciable inelastic scattering contributions and extended over a somewhat limited angular range.

Above 2.5 MeV the evaluation relies entirely upon the model of Ref. III-1. That model is known to be very descriptive of elastic scattering from the analogous nucleus, ^{238}U (III-1). It is also descriptive of the total cross section of thorium, as outlined in Sec. II above, and can be reasonably verified over the energy range 1.5 to 2.6 MeV using the recent measurements of Refs. III-5 and -8. Such verification is illustrated in Fig. III-1. Except for the details of the shape of the second diffraction minimum, the model agrees very well with the measured values and provides a mechanism for extrapolating beyond the measured angular range. The angle-integrated elastic scattering cross sections given by the model agree to within 10 percent with those obtained from an empirical fit to the data of Refs. III-5 and -8. The model (and thus the evaluation) tend to be a bit larger in cross section magnitude than the cross sections obtained directly from the measurements thus implying smaller inelastic scattering cross sections than do the direct measurements. At higher energies (above 2.5 MeV) the model can be checked against the measurements of Smith et al. (III-5), Batchelor and Towle (III-9), Buccino et al. (III-11) and Hudson et al. (III-12). All of these latter measurements contained varying inelastic-scattering contributions. Thus the comparisons with the measurements were made with the inclusion of estimated inelastic scattering contributions in the calculated results. Illustrative comparisons with these measured values are shown in Fig. III-2. The model-deduced results (i.e., the evaluation) agree reasonably well with the measured values. Perhaps the largest differences are near 15 MeV but even there the differences are at large scattering angles where the cross section is very small and thus of minor applied importance. The systematic behavior of the evaluated elastic-scattering distributions is illustrated in Fig. III-3.

The uncertainties associated with the evaluated angle-integrated elastic scattering cross sections are estimated to be $\lesssim$10 percent. Such uncertainties are frequently much smaller than the differences between the present evaluation and that of ENDF/B-IV as illustrated in Fig. III-4. The present evaluated neutron total and elastic-scattering cross sections define a nonelastic cross section which reaches a maximum value of $\cong$3.7 b at $\cong$2.5 MeV with an uncertainty of ±10 percent. This nonelastic cross section implies a total inelastic scattering cross section of $\cong$3.5 b ± 10-15 percent at 2.5 MeV. More generally, the nonelastic cross section places relatively stringent limits on the total inelastic scattering cross section at energies below the (n;2n') threshold.

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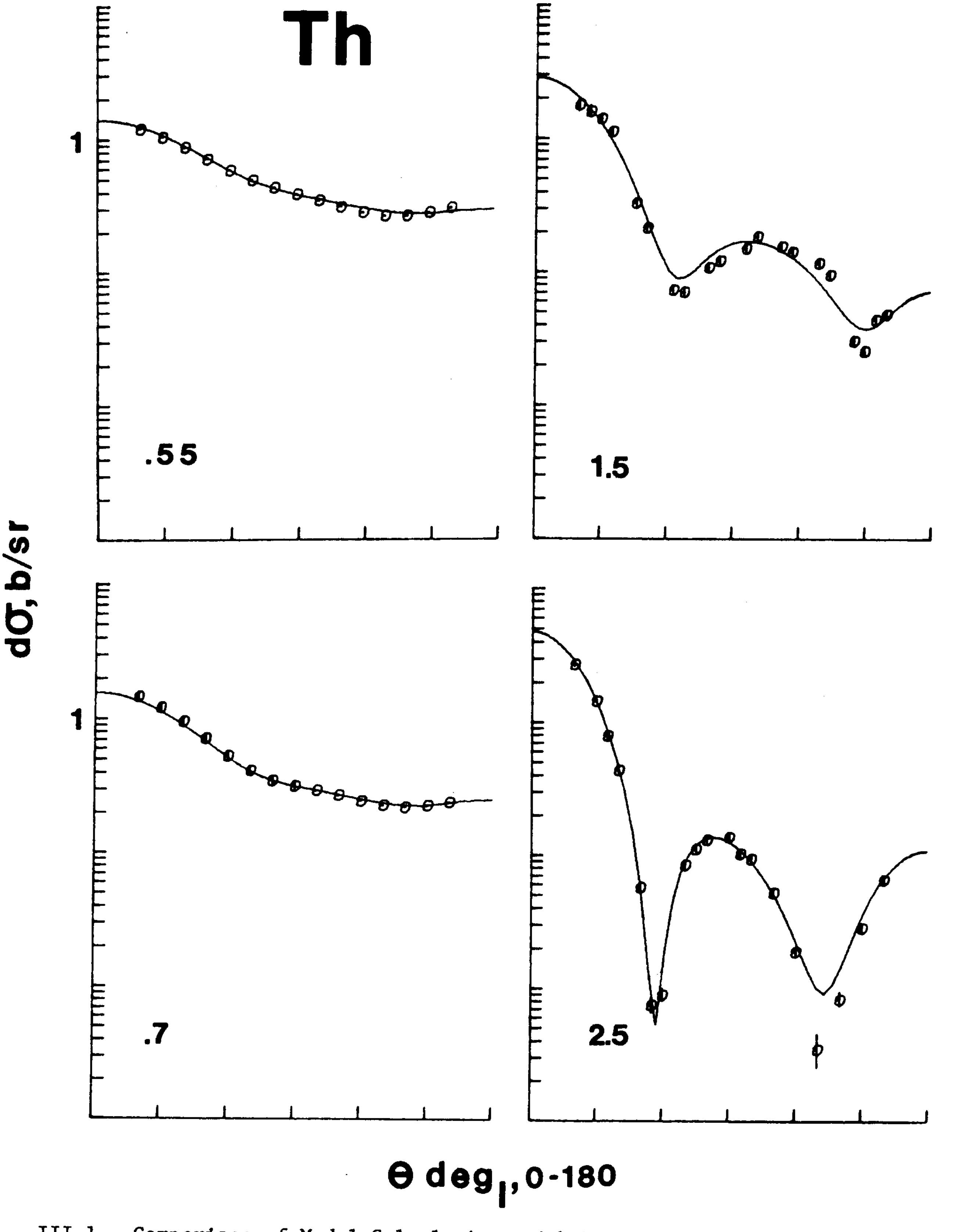
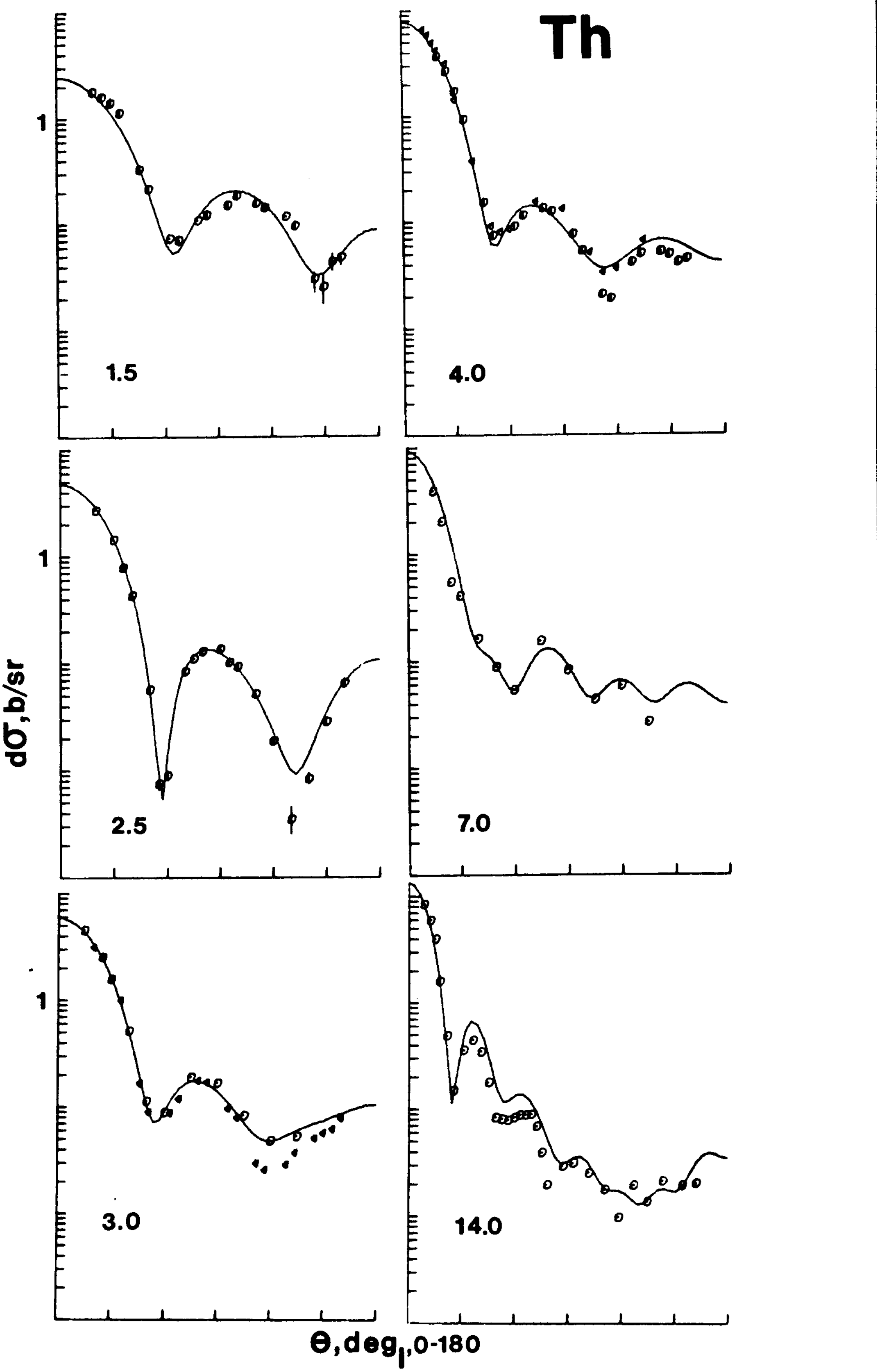
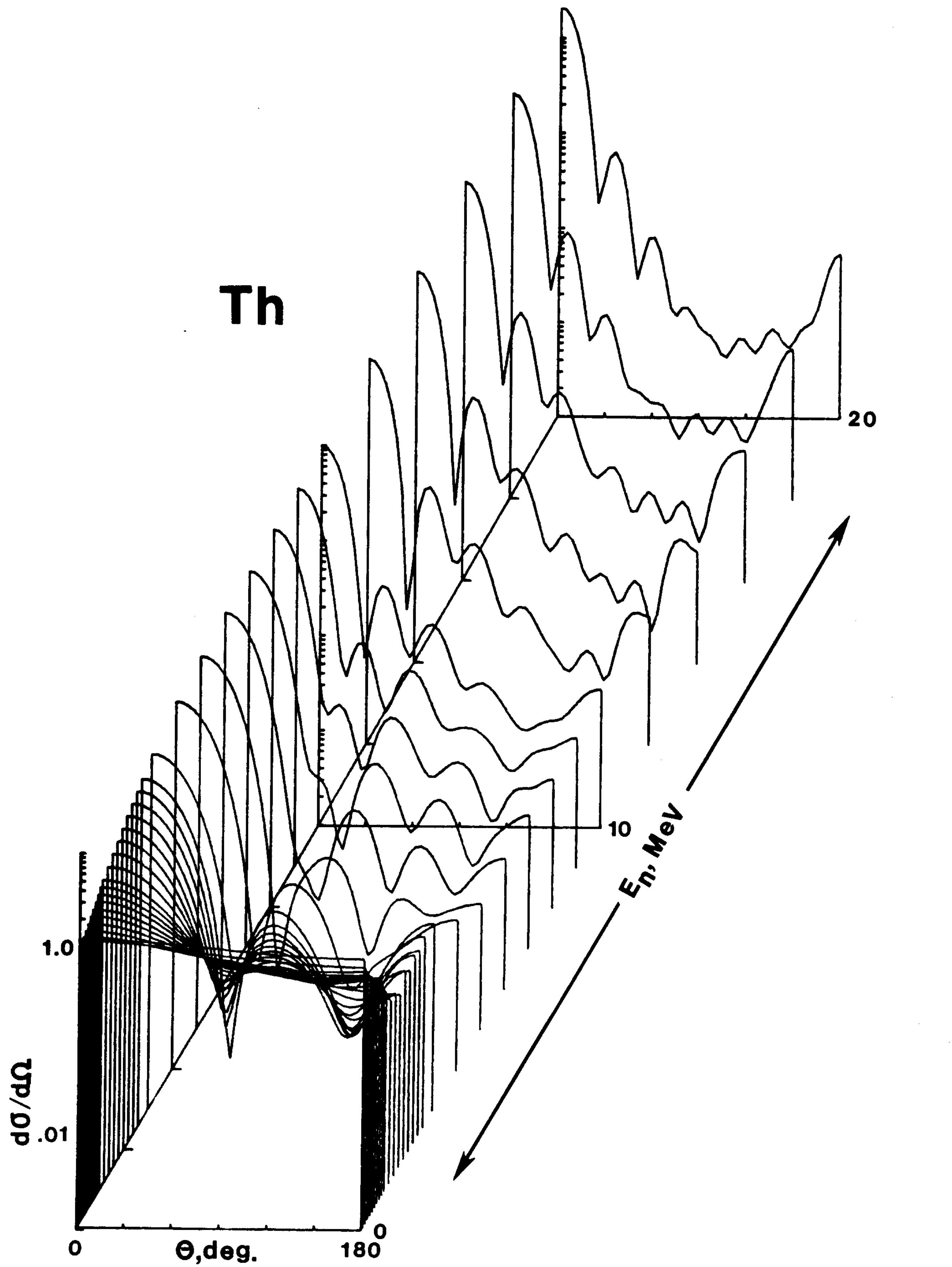


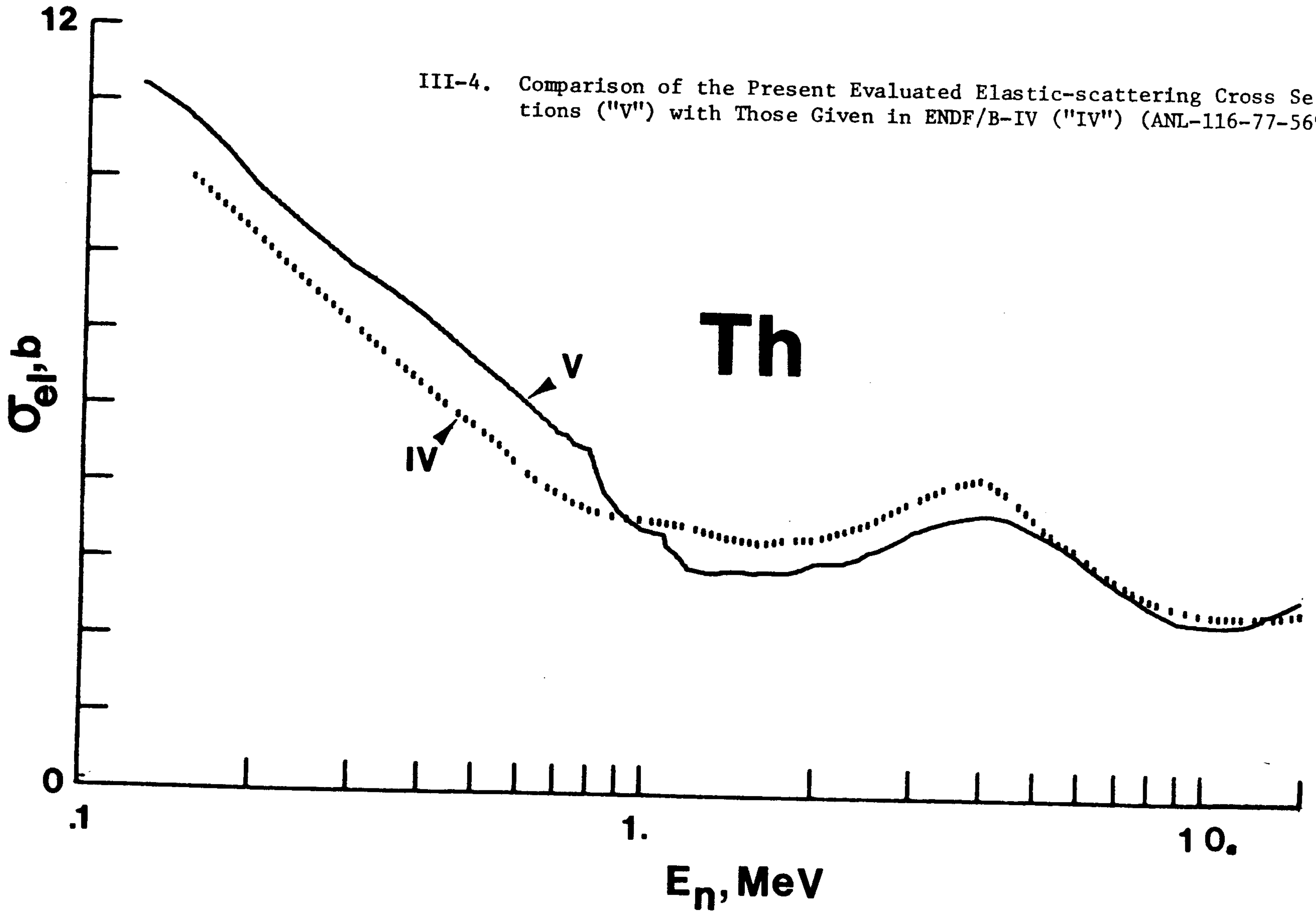
III-1. Comparison of Model Calculations with Measured Data Values Taken from Refs. III-5 and III-8 (ANL-116-77-507).



III-2. Comparison of the Present Evaluation with Measured Results. Curves indicate the evaluation. Data points are taken from references outline in the text. Inelastic scattering contributions were included in the calculated results as indicated by experiments (ANL-116-77-573)

III-3. Systematic Energy-angle Behavior of the Evaluated Elastic-scattering Cross Sections (ANL-116-77-525).





III-4. Comparison of the Present Evaluated Elastic-scattering Cross Sections ("V") with Those Given in ENDF/B-IV ("IV") (ANL-116-77-569).

IV. NEUTRON INELASTIC SCATTERING

The evaluation in this area consists of discrete-inelastic-excitation cross sections and cross sections for the excitation of a continuum of states. The branch point between the reaction types is 1250 keV with some energy overlap to provide a smooth transition between the two types of processes. The evaluation is based upon the available limited experimental information extrapolated and interpolated with theory.

Discrete-Inelastic Neutron Scattering

The experimental data base is limited--consisting largely of the results of Smith (IV-1), McMurray et al. (IV-2), Haouat et al. (IV-3), Batchelor and Towle (IV-4 and IV-5) and Smith et al. (IV-6 and IV-7). The most comprehensive of these results is from McMurray et al. and include both direct measurements of (n;n') cross sections and observation of gamma-rays from the (n;n',γ) process. The latter give particularly detailed definition of the excited structure of ^{232}Th and these results, augmented by existing charged-particle results, are the basis for determining the excitation energies for the present evaluation (IV-8). The known level structure is very complex with an average level spacing of $\lesssim$35 keV over the first 1500 keV of excitation and even that observed estimate is very likely representative of too few levels. Some of these excited states are separated by a keV or less. Such separations are of little applied importance. Moreover, the inclusion of all reported structure would result in an awkwardly large evaluated file. Therefore, the present evaluation groups the excited structure into mean excitation-energy intervals as defined in Table IV-1. The selection is consistent with the best resolution measurements of (n;n') scattering and provides an energy definition suitable for most applications. Table IV-1 correlates the structure of the evaluation with the individual observed states and, where possible, with reported

KJΠ values. ^{232}Th is an even and deformed actinide nucleus and shows many of the collective properties of such nuclei. However, the nucleus is unusual in that many of the collective-band heads (e.g., β-vib., γ-vib., Octupole) set in at excitations of 700-800 keV. As a consequence the inelastic-neutron-scattering cross section rises rapidly in this energy range with a consequent impact on the elastic scattering process.

The first three inelastic-neutron groups (49.5,2+; 162.5,4+; and 333.0,6+) are clearly due to the excitation of the ground-state rotational band. The last (333.0,6+) is weakly excited so higher orders of the band are ignored and will generally appear as components of groups corresponding to higher excitation energies. The evaluation is based upon the experimental results of Refs. IV-1, 2, 3, 6, and 7 with primary emphasis on Ref. IV-2. The model of Ref. IV-9 was used for extrapolation to 20 MeV and for interpolation between measured values. This is a coupled-channel model including direct-reaction contributions. The angular distributions were based upon the model-extrapolated experimental results to incident energies of $\leq$2.5 MeV and were based on the model alone at higher energies. The emitted-neutron angular distributions are anisotropic at higher energies and quantitatively consistent with the observed results of Refs. IV-3 and -7. An exception is the distributions due to the excitation of the 6+ state which was simplified to isotropy due to the small magnitude of the corresponding cross sections. The evaluation (here and elsewhere) is generally consistent with the (n;n',γ) results of Ref. IV-2 but the (n;n',γ) results were not used in the evaluation of inelastic-scattering cross sections due to uncertainties in branching ratios both within and between bands. The present evaluation is compared with the data base and the comparable ENDF/B-IV evaluation in Fig. IV-1. The two evaluations are very different, particularly at higher energies where ENDF/B-IV does not contain the direct-reaction components indicated by both theory and experiment.

The fourth inelastic group consists of contributions from the excitation of 730- and 714-keV states with a mean excitation energy of 722 keV. The respective measured cross sections are given in Refs. IV-2, -6, and -7. The group with a mean excitation of 793 keV is attributed to contributions from 774.1, 774.3, 785.3 and 829.7 keV states. Relevant cross sections are reported in Refs. IV-2, -6, and -7. References IV-1, -4, and -5 further report cross sections for the collective excitation of the two states, (722 and 793 keV). This data base and the respective evaluations are outlined in Fig. IV-2. The large majority of the measured values are consistent with the evaluation to within ±10 percent. The respective angular distributions of the scattered neutrons are given an anisotropy at higher energies equivalent to that observed by Kammerdiener (IV-10) in the scattering of $\tilde{-}$14.5 MeV neutrons from the similar nucleus ^{238}U. Generally, throughout this evaluation, the angular dependence and high-energy behavior of the discrete inelastic excitation functions are similar to those of ^{238}U as described in Ref. IV-11. The ^{238}U nucleus is similar to ^{232}Th and there are both microscopic and macroscopic experimental values for ^{238}U. These, together with theory, serve as reasonable guidelines in regions where there is no ^{232}Th experimental information.

The fifth and sixth mean excitations (E_x = 882.3 and 950.3 keV, respectively) are relatively weak. At least the former is a composite of contributions from several states. The evaluation is based on the measured values of Ref. IV-2 with the results illustrated in Fig. IV-2.

The eighth and ninth groups (E_x = 1081 and 1137 keV, respectively) are again composites. Experimental values are available from Refs. IV-2, -4, -6, and -7. The cross sections are relatively large as indicated in Fig. IV-2. The remaining experimentally-measured cross sections are associated with mean excitations of 1182 and 1213 keV. Four additional excitations are introduced in the evaluation (E_x = 1300, 1375, 1425, and 1450 keV) in order to blend the discrete-inelastic portion of the file smoothly into the continuum-inelastic component. These final four excitations do not explicitly correspond to measured values but are reasonable estimates in both magnitude and position.

Below 1250 keV the above discrete-inelastic-scattering components must sum to a total inelastic scattering cross section consistent, to within uncertainties, with the above-cited nonelastic cross sections. The largest discrepancies are $\leq$10 percent.

Continuum-Inelastic-Neutron Scattering

This portion of the evaluation starts the cross section for inelastic neutron scattering to a continuum of unresolved states at an excitation of 1250 keV. Thus, these cross sections somewhat overlap and blend with those due to discrete inelastic-scattering excitation functions (above). The magnitudes of the continuum inelastic scattering cross sections were fixed by the nonelastic cross section and the remaining partial cross sections. The latter contributions were reasonably known and/or small up to incident energies of $\simeq$15 MeV and thus fix the continuum-inelastic-scattering cross sections to within 10-20 percent in regions of appreciable magnitude. Above 15 MeV the (n;3n') cross section is large and not well known. As a consequence the uncertainties in the continuum-inelastic scattering increase above 15 MeV.

The spectra of neutrons emitted in the continuum-inelastic process are based upon the measured evaporation temperatures as outlined in Table IV-2. In addition, a harder component due to precompound processes was added, increasing from a negligible amount at 6 MeV to approximately 20 percent at 20 MeV. This precompound component was patterned after that of the ^{238}U evaluation of Ref. IV-9. Additional adjustments were made as the result of integral tests at $\simeq$14.5 MeV as described in Sec. XI and Ref. IV-12. The evaluation assumes isotropic inelastic neutron emission including the precompound component. That assumption is crude at best but there is apparently no alternative using presently accepted ENDF formats.

The present evaluated inelastic continuum cross sections and emission spectra are very much different from those given in ENDF/B-IV as illustrated in Fig. IV-3. The differences are well beyond the indicated 10-15 percent error associated with the present evaluation in regions where the cross sections are of significant magnitude.

The cumulative sum of the above components, of course, gives the total inelastic scattering cross section. This total value is compared with the comparable values from ENDF/B-IV in Fig. IV-4. The differences between the two evaluations are large in regions of large cross section and exceed the ~10-15 percent uncertainties associated with the present evaluation over much of the energy range.

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TABLE IV-1. Inelastic-Neutron-Excitation Energies

Level Nº	E_x (keV)	E-Thres. (keV)	Comments
1	49.5	49.7	(0,2+) ground-state rotational band
2	162.5	163.2	(0,4+) ground-state rotational band
3	330.0	334.4	(0,6+) ground-state rotational band
4	722.0	725.1	Sum of: 730.4 (0,0+) β-vib. 714.3 (0,1-) Octupole, K=0
5	793.0	796.4	Sum of: 774.1 (0,2+) β-vib. 774.3 (0,3-) Octupole, K=0 785.3 (2,2+) γ-vib, K=2(?) 829.7 (3) γ-vib, K=2(?)
6	882.3	886.1	Sum of: 873.1 (0,4+) β-vib 883.3 (0,5-) Octupole, K=0 890.4 (4) γ-vib, K=2(?)
7	950.3	954.4	(5,?) single state
8	1081.0	1086.0	Sum of: 1053.9 (2-) 1073.3 (2+) 1077.7 (1-) 1078.8 (?) 1095.0 (?) 1106.0 (?) 1148.0
10	1182.0	1187.0	Single state
11	1213.0	1218.0	Sum of: 1208.0 1218.0
12	1300.0	1306.0	Estimated "mean"
13	1375.0	1381.0	Estimated "mean"
14	1425.0	1431.0	Estimated "mean"
15	1450.0	1456.0	Estimated "mean"

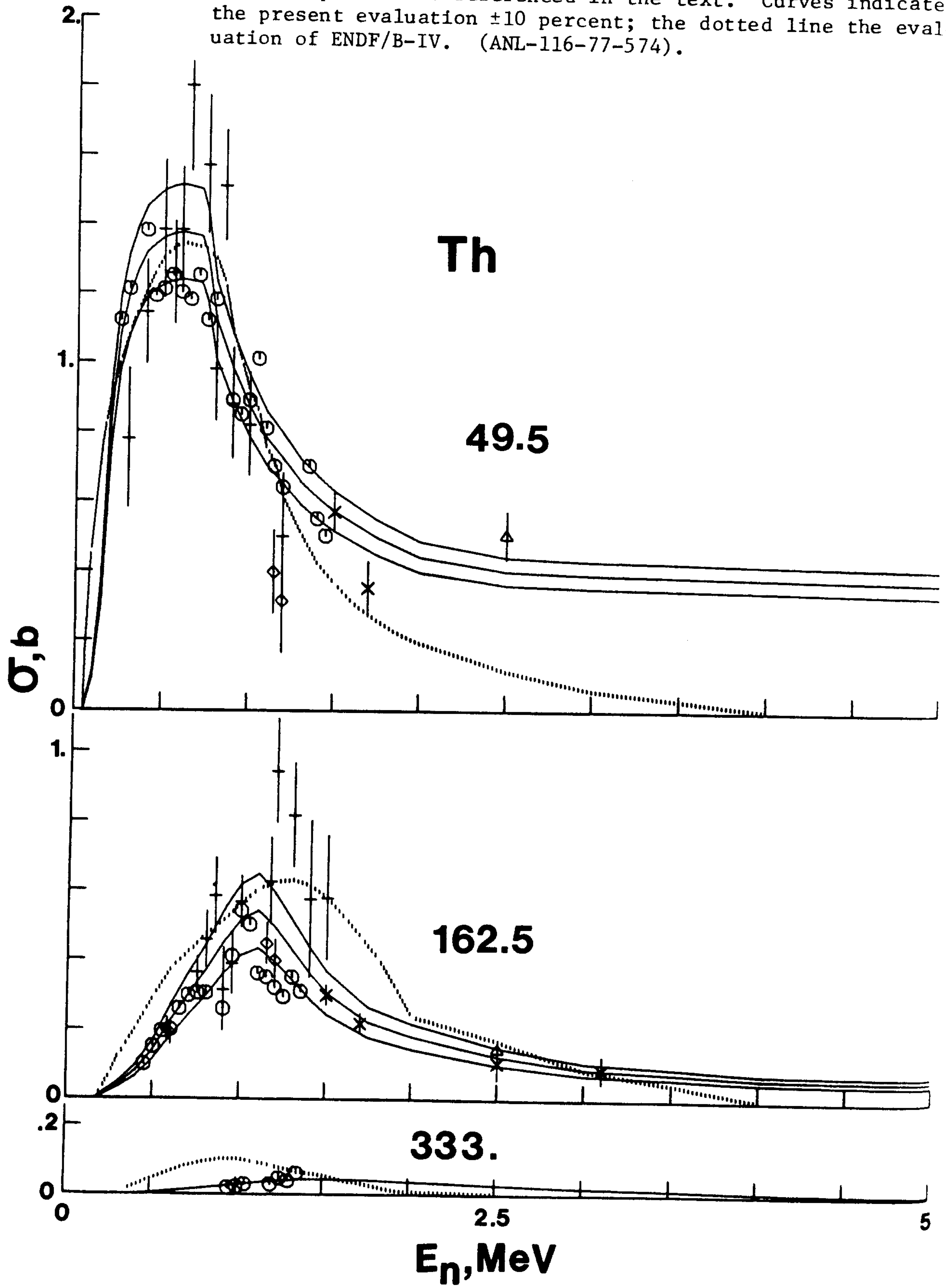
*Continuum starts at 1250 keV.

TABLE IV-2. Continuum-Inelastic Scattering Temperatures[a]

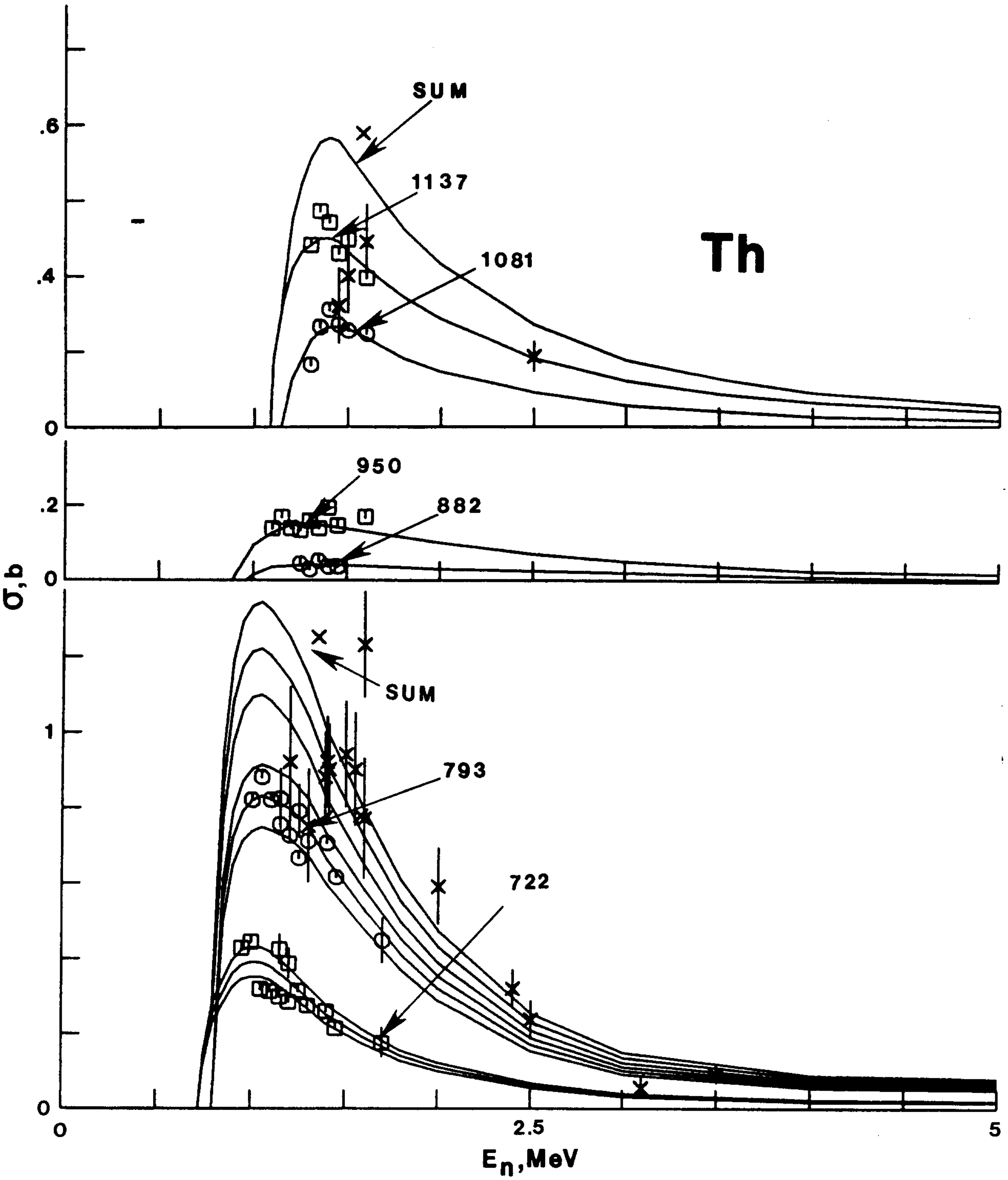
E (MeV)	Temperature (MeV)	Ref.
3.0	0.41 ± 0.04	b
3.1	0.43 ± 0.05	c
3.3	0.45 ± 0.05	c
3.5	0.40 ± 0.05	c
3.7	0.50 ± 0.05	c
3.9	0.49 ± 0.05	c
4.0	0.46 ± 0.05	b
7.0	0.53 ± 0.05	b

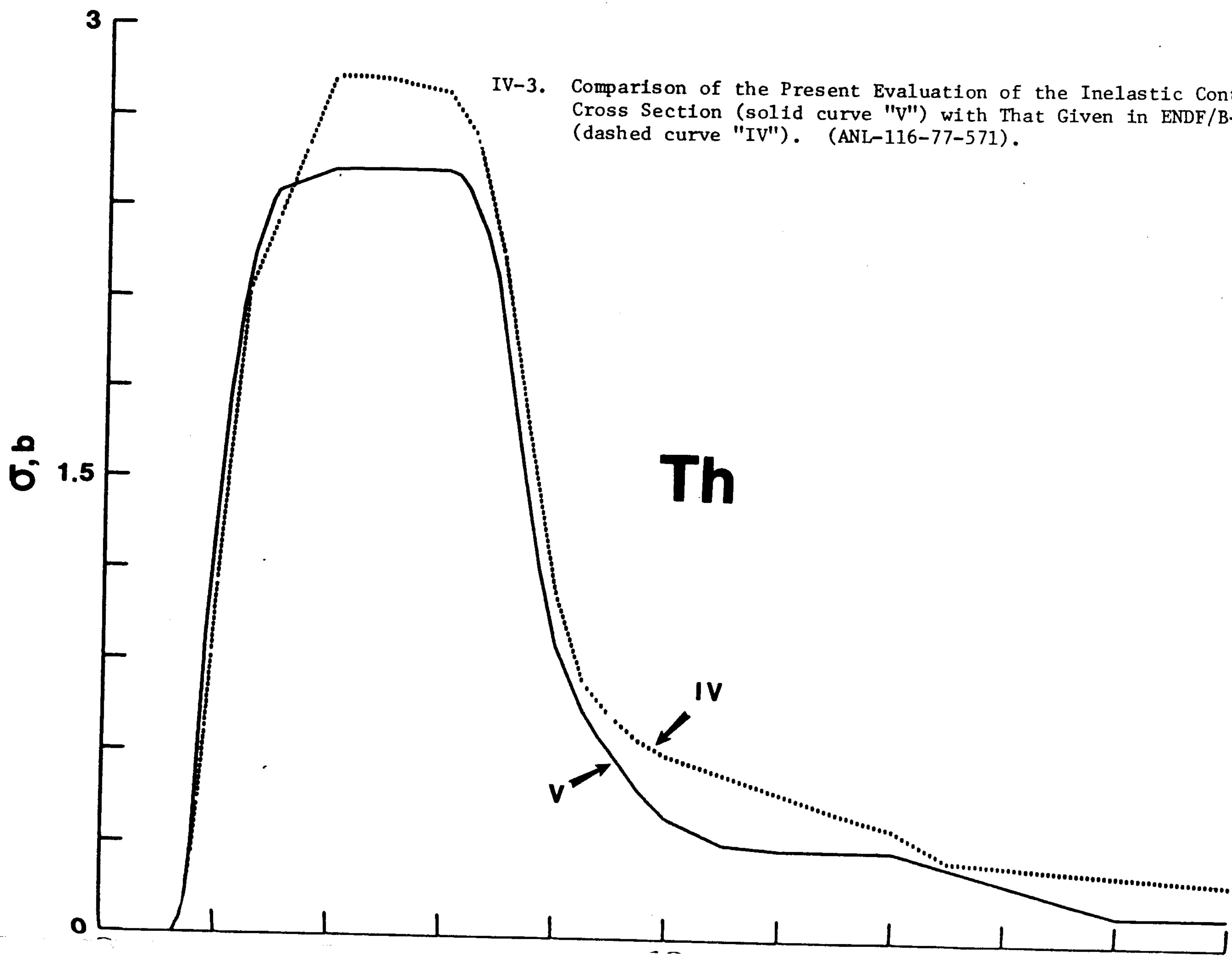
[a]Temperature distribution is assumed to be of the form $N(E) \sim E \exp(-E/T)$ and $T=a\cdot E$ where $a=0.1257$.
[b]Data from R. Batchelor and J. Towle, Nucl. Phys., *65* 236 (1965).
[c]Data from A. Smith et al., private communication (1977).

IV-1. Comparison of Measured and Evaluated Cross Sections for the Excitation of 49.5, 162.5, and 333.0 keV States in the ^{232}Th. The data points are referenced in the text. Curves indicate the present evaluation ±10 percent; the dotted line the evaluation of ENDF/B-IV. (ANL-116-77-574).



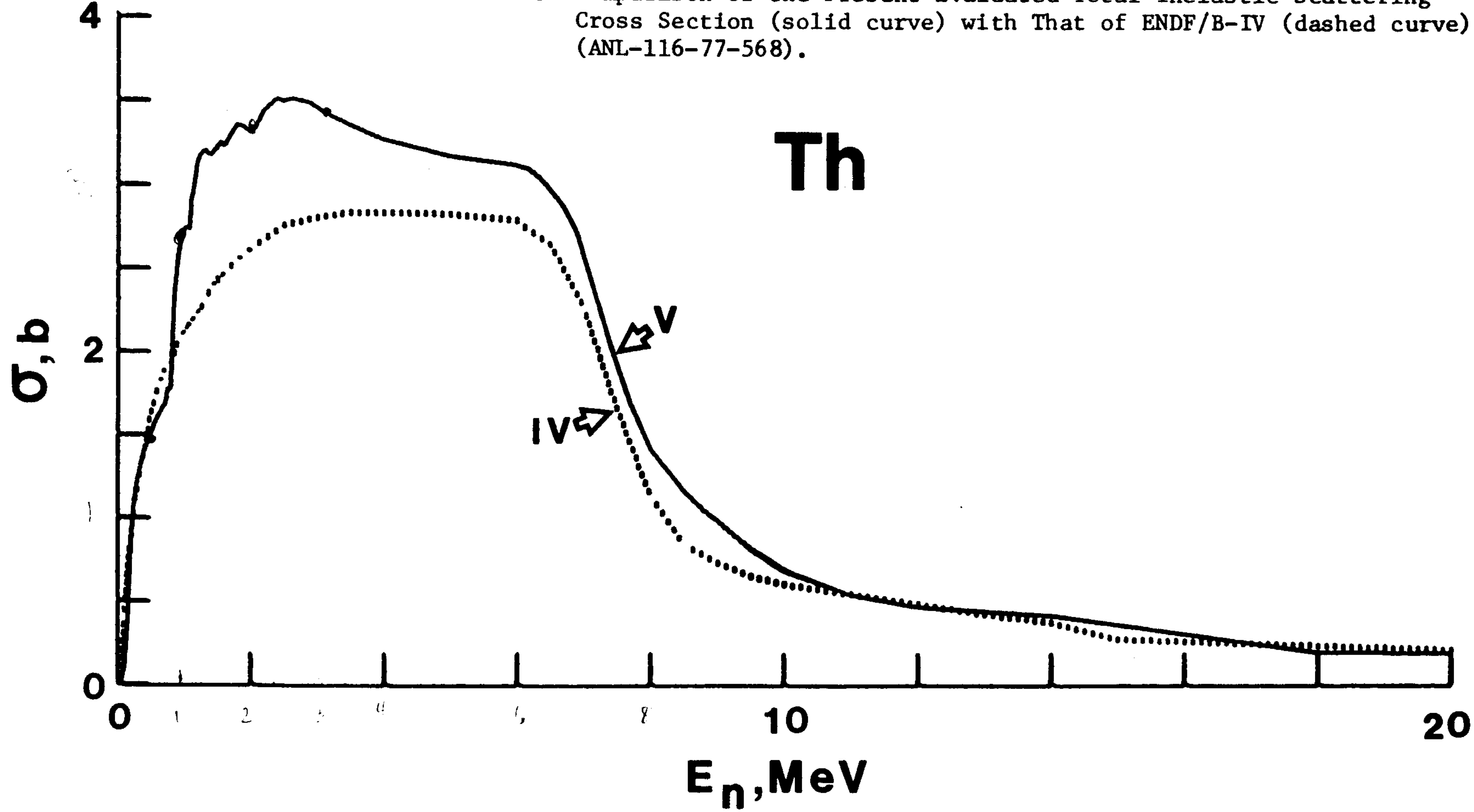
IV-2. Comparison of Measured and Evaluated Cross Sections for the Excitation of 722, 793, 882, 980, 1081, and 1137 keV States. Data points are referenced in the text. Curves indicate the present evaluation (±10 percent error-bands are also given for the lowest two levels). (ANL-116-77-512).





IV-3. Comparison of the Present Evaluation of the Inelastic Continuum Cross Section (solid curve "V") with That Given in ENDF/B-IV (dashed curve "IV"). (ANL-116-77-571).

IV-4. Comparison of the Present Evaluated Total Inelastic Scattering Cross Section (solid curve) with That of ENDF/B-IV (dashed curve). (ANL-116-77-568).



V. NEUTRON FISSION CROSS SECTIONS

Data Base

The existing ^{232}Th (n;f) data base is of rather dubious quality. Some data are listed in the NNDC files. Other data were obtained from graphs of original or secondary publications, as well as by private communication. Of the five more recent measurements (Refs. V-11, -13, -15, -16, and -17) only one data set has been published (V-11, in a graph), two are preliminary (V-15 and -16), and the other two (V-13 and -17) are not yet available. Several data sets are only available as graphs. For several others the reference cross sections used to convert measured ratios to ^{232}Th (n;f) cross sections are uncertain; error quotations open to interpretation, and/or descriptions of experimental procedures unavailable. Several sets of data were measured with basic nuclear physics phenomena in mind. Exclusion of all preliminary, undocumented and doubtfully referenced data sets would have left the file without sufficient data for any meaningful evaluation. Therefore, all data were accepted on an equal base, assuming experimenters have responsibly distributed their data and that the evaluator had to make estimates dealing with uncertain and/or missing information. The available data files are summarized in Tables V-1 to V-4.

Procedure

The present evaluation followed the same procedure as used in the recent evaluation of ^{238}U (n;f) and ^{238}U (n;γ) for ENDF/B-V (V-1). Ratios of ^{232}Th (n;f)/^{238}U (n;f), ^{232}Th (n;f)/^{235}U (n;f), and absolute values of ^{232}Th (n;f) were evaluated first. The proposed ENDF/B-V cross sections for ^{238}U (n;f) and ^{235}U (n;f) were used to convert the evaluated ratios to ^{232}Th (n;f) cross sections. The resulting three cross section sets are not quite independent, since the ^{235}U (n;f) and ^{238}U (n;f) cross sections of ENDF/B-V are interdependent.

Since uncertainties in the ^{238}U (n;f) and ^{235}U (n;f) values are generally small compared with large uncertainties in ^{232}Th (n;f) measurements, the assumption that any bias introduced by the interdependence is within the uncertainty of the evaluated cross section is justified. The result of the present evaluation is the weighted average of these three cross-section sets (see Fig. V-1).

The ^{232}Th (n;f)/^{238}U (n;f) Ratio

The separate evaluation of data on the ^{232}Th (n;f)/^{238}U (n;f) ratio is especially appealing as both are similar threshold reactions. Background and scattering corrections should be of a similar nature and the chance of errors due to these effects should be reduced. Unfortunately the available data sets are restricted to narrow energy ranges. Most important is the comparison at 14.2 MeV which is shown in Fig. V-2. The experimental values agree rather well with the weighted average of 0.304 ± 0.008.

The ^{232}Th (n;f)/^{235}U (n;f) Ratio

The data for the ^{232}Th (n;f)/^{235}U (n;f) ratio are mainly based on the preliminary sets by Behrens et al. (V-15) and by Blons et al. (V-16). The latter are only a shape measurement and their quoted uncertainty is unclear. The former authors quote the lowest uncertainty and thus have the highest weight in the present evaluation. No description of the measurements by Behrens et al. is yet available. However, the data were accepted with their high weight based on the good agreement of the ^{238}U (n;f)/^{235}U (n;f) ratio data by Behrens et al. with the evaluated ratio for this quantity (see Ref. V-1). The data by Ermagambetov et al. (V-19) were measured relative to natural uranium thus below 840 keV ^{235}U (n;f) is the predominant reference cross section and above this energy it is the ^{238}U (n;f) cross section. The major interest in these data was in their shape at low energies; therefore the values were converted to ^{232}Th (n;f)/^{235}U (n;f) ratio data over the total energy range. This seems justified due to the close relationship between ^{238}U (n;f) and ^{235}U (n;f) (see Ref. V-1).

The shape difference between the data by Behrens et al. (V-15) and by Blons et al. (V-16) was ≈20 percent with the data by Ermagambetov et al. (V-19) usually in support of the Blons et al. data. The differences may be due to an energy scale difference and one would tend to believe the energy scale of Behrens et al. - again based on their correct ^{238}U (n;f)/^{235}U (n;f) measurements. However, no corroborating measurement is available and no data set was shifted in energy.

The energy grid for the present evaluation was chosen with such a density as to permit the representation of broader structure in the ^{232}Th (n;f) cross section. The possible additional information available with the high resolution data by Blons et al. (V-16) was ignored because no corroborative measurements are available and such structure has little practical importance in nuclear-data-file applications.

Absolute normalization of the arbitrarily normalized shape of the ^{232}Th (n;f)/^{235}U (n;f) ratio data was obtained from the data by Behrens et al. (V-15) (factor of 1.000), Henkel et al. (V-12) (factor of 0.962), and Williams et al. (V-18) (factor of 0.994); all values compared to the weighted average 0.993.

Absolute ^{232}Th (n;f) Cross Sections

Measurements of ^{232}Th (n;f) independent of other cross sections or relative to the well-known H(n;n) cross section were mainly restricted to shape measurements, the exceptions being a measurement by Ladenburg et al., (V-14) in 1939 and by Potopopov et al. (V-9) at 14.6 MeV. Several sets by Kalinin and Pankratov (V-10) were combined and renormalized in overlapping energy ranges. Data by Henkel et al., (V-12) were shape measurements relative to a

Long Counter, ratio measurements relative to ^{235}U (n;f) at 2.8 and 4.0 MeV were included in the evaluation of the ^{232}Th (n;f)/^{235}U (n;f) ratio.

Discussion and Comparison

Illustrative results from the present evaluation are given in Table V-5. The ^{232}Th (n;f) cross sections derived from $^{232}Th/^{238}U$ ratios and from $^{232}Th/^{235}U$ ratios agree reasonably well with the evaluated cross section. Absolute ^{232}Th (n;f) data do not agree as well as there is a difference in shape between low energies (<1.5 MeV) and high energies (>13 MeV). An interesting comparison of the absolute values can be made at 14.6 MeV:

$^{232}Th/^{235}U$, Behrens et al., (V-15) *^{235}U, ENDF/B-V	0.411 ± 0.024 b
^{232}Th, absolute, Protopopov (V-9)	0.35 ± 0.02 b
$^{232}Th/^{238}U$, average value from Fig. 2, corrected to 14.6 MeV, * ^{238}U, ENDF/B-V	0.382 ± 0.021 b

This comparison suggests that some more data for the normalization of ^{232}Th (n;f) cross sections are desirable.

Figures V-3 and V-4 compare the evaluated ^{232}Th (n;f) cross section with those derived from the ratio measurements by Behrens et al., (V-15) and by Blons et al., (V-16) by utilizing the ^{235}U (n;f) cross section of ENDF/B-V. The figures suggest an investigation of the energy scale in the threshold region. Existing, but not yet available data (Nordborg (V-17), Poenitz (V-13)) are expected to contribute to the solution of the normalization problem but not to that of the energy scale problem.

Present uncertainties in the knowledge of the ^{232}Th (n;f) cross section are typically 5-10 percent but much larger in the threshold region. However, due to their small values, ^{232}Th (n;f) cross sections are of less importance to reactor neutronics in $^{233}U/^{232}Th$ systems than ^{238}U (n;f) in $^{239}Pu/^{238}U$ systems. Uncertainty guidelines associated with the present evaluation are given in Table V-5. Exact tabular uncertainty values can be obtained from the authors.

A comparison with ENDF/B-IV (V-24) is shown in Fig. V-5. Below and including 1.2 MeV the ^{232}Th (n;f) cross section is set to zero in ENDF/B-IV, ignoring the then available data by Ermagambetov et al., (V-19). Differences in the threshold range are up to a factor two. Between 7 and 13 MeV differences are in the 10-15 percent range, otherwise agreement of ENDF/B-IV with the present evaluation is usually within 10 percent.

The average cross section corresponding to the present evaluation and the reference ^{235}U fission-neutron spectrum adopted for ENDF/B-V (a Maxwellian distribution with temperature 1.32 MeV) was calculated and found to be 72.8 mb. This value is larger than the 69.0 mb value for the ENDF/B-IV evaluated fission cross section and in better agreement with recently reported integral values (V-25 through V-29). The latter fall in the range 71-83 mb.

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TABLE V-1. Summary of ^{232}Th (n,f)/^{238}U (n,f) Ratio Data

Set		Ref.	Source	Type, Use	Range	Status
1	Barrall	III-20	Report, CSISRS	Normalization	14.6 MeV	O.K.
2	Nyer	III-2	CSISRS	Normalization	14 MeV	O.K.
3	Iyer	III-3	CSISRS	Normalization	14.1 MeV	O.K.
4	Taschek	III-4	Secondary Report	Shape, Normalization (assumed)	1.2 - 1.9 MeV	Unknown
5	Berezin	III-5	CSISRS	Normalization	14.6 MeV	O.K.
6	Uttley	III-6	CSISRS	Normalization	14.1 MeV	O.K.
7	Rago	III-7	CSISRS	Shape, Normalization	12 - 18 MeV	O.K.
8	Babcock	III-8	CSISRS	Shape, Normalization	1.1 - 1.8 MeV, 13 - 18 MeV	Unknown
9	Phillips	III-23	Report	Normalization	14 MeV	O.K.

TABLE V-2. Summary of ^{232}Th (n,f)/^{235}U (n,f) Ratio Data

Set	Ref.	Source	Type, Use	Range	Status
1. Behrens	III-15	Report	Shape, Normalization	0.7 - 3.2 MeV	Preliminary
2. Henkel	III-12	Report	Normalization	2.8, 4.0 MeV	Partly unclear
3. Blons	III-16	CSISRS	Shape	1.2 - 5 MeV	Partly unclear
4. Nordborg	III-17	--	Shape, Normalization		Not yet available
5. Williams	III-18	CSISRS	Normalization	3.4, 4.8, 5.85 MeV	available
6. Ermagambetov	III-19	Publication, Graph	Shape	0.6 - 3 MeV	available

TABLE V-3. Summary of Absolute ^{232}Th (n,f) Data

	Set	Ref.	Source	Type, Use	Range	Status
1.	Protopopov	III-9	CSISRS	Normalization	14.6 MeV	available
2.	Pankratov, Kalinin	III-10	CSISRS, Publication Graph	Shape	3 - 37 MeV	available partly unclear
3.	Konecny	III-11	Publication, Graph	Shape	1.2 - 1.9 MeV	available partly unclear
4.	Henkel	III-12	CSISRS, Report	Shape	1.2 - 9 MeV	available partly unclear
5.	Poenitz	III-13	--	Shape, Normalization	1.2 - 8.5 MeV	Not yet available
6.	Ladenburg	III-14	Publication	Normalization (assumed absolute)	2.4 MeV	available

TABLE V-4. Summary of Other Data on ^{232}Th (n,f)
(not used in the present evaluation)

	Set	Ref.	Source	Reference Cross Section
1.	Muir	III-21	CSISRS	^{239}Pu (n,f)
2.	Behkami	III-22	Publication	^{236}U (n,f)
3.	Poenitz	III-13	--	^{233}U (n,f)

TABLE V-5. Illustrative ^{232}Th (n,f) Results from the Present Evaluation

E(MeV)	σ(b)	Δσ(b)
.6000E 00	.1103E-04	.6000E-05
.8000E 00	.1310E-03	.1200E-04
.9000E 00	.5200E-03	.8000E-04
.1000E 01	.1240E-02	.6000E-04
.1200E 01	.5220E-02	.4000E-03
.1400E 01	.5600E-01	.2000E-02
.1600E 01	.1140E 00	.4000E-02
.1800E 01	.7700E-01	.6000E-02
.2000E 01	.1180E 00	.5000E-02
.2500E 01	.1160E 00	.8000E-02
.3000E 01	.1330E 00	.5000E-02
.4000E 01	.1470E 00	.6000E-02
.6000E 01	.1540E 00	.1200E-01
.8000E 01	.3680E 00	.3800E-01
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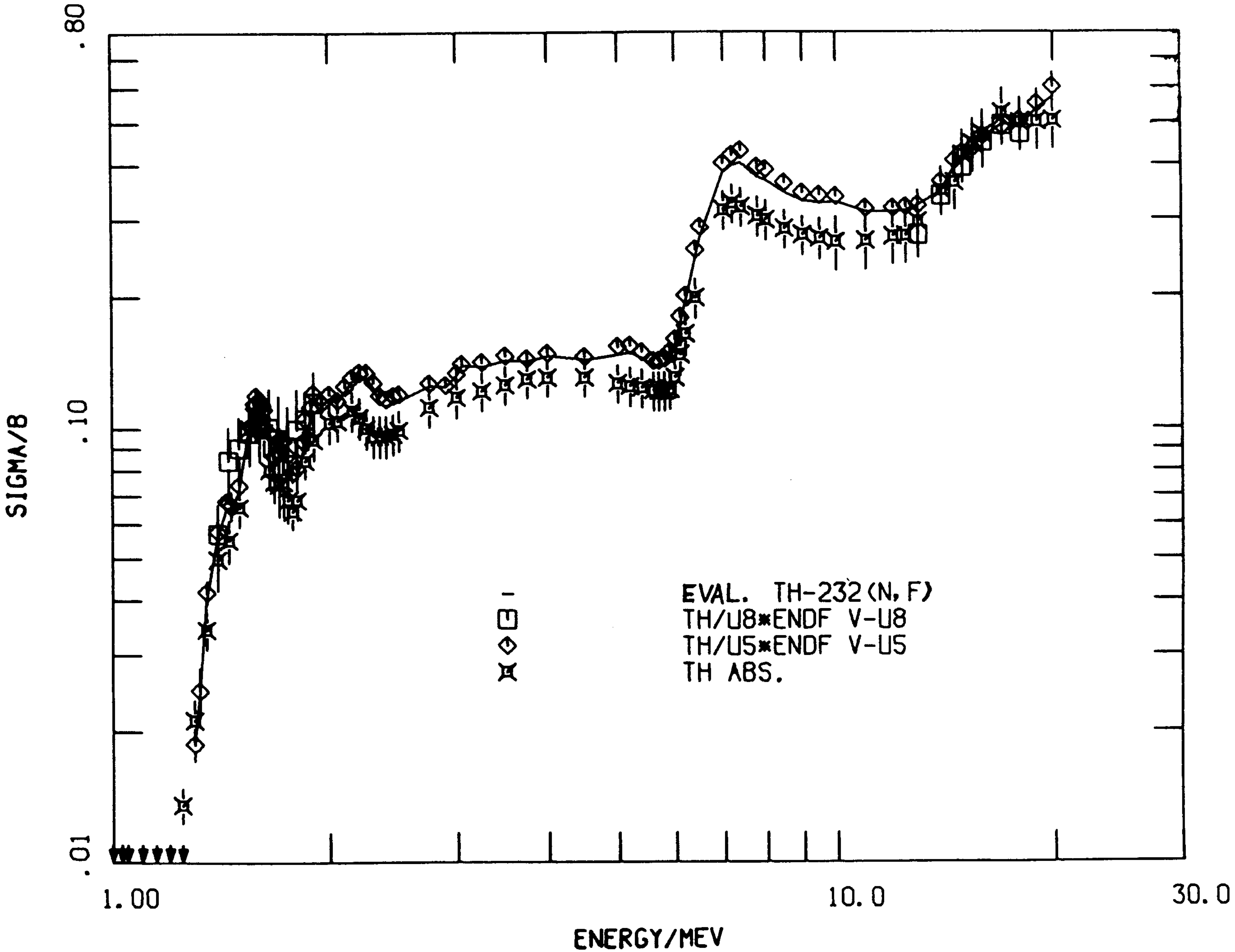
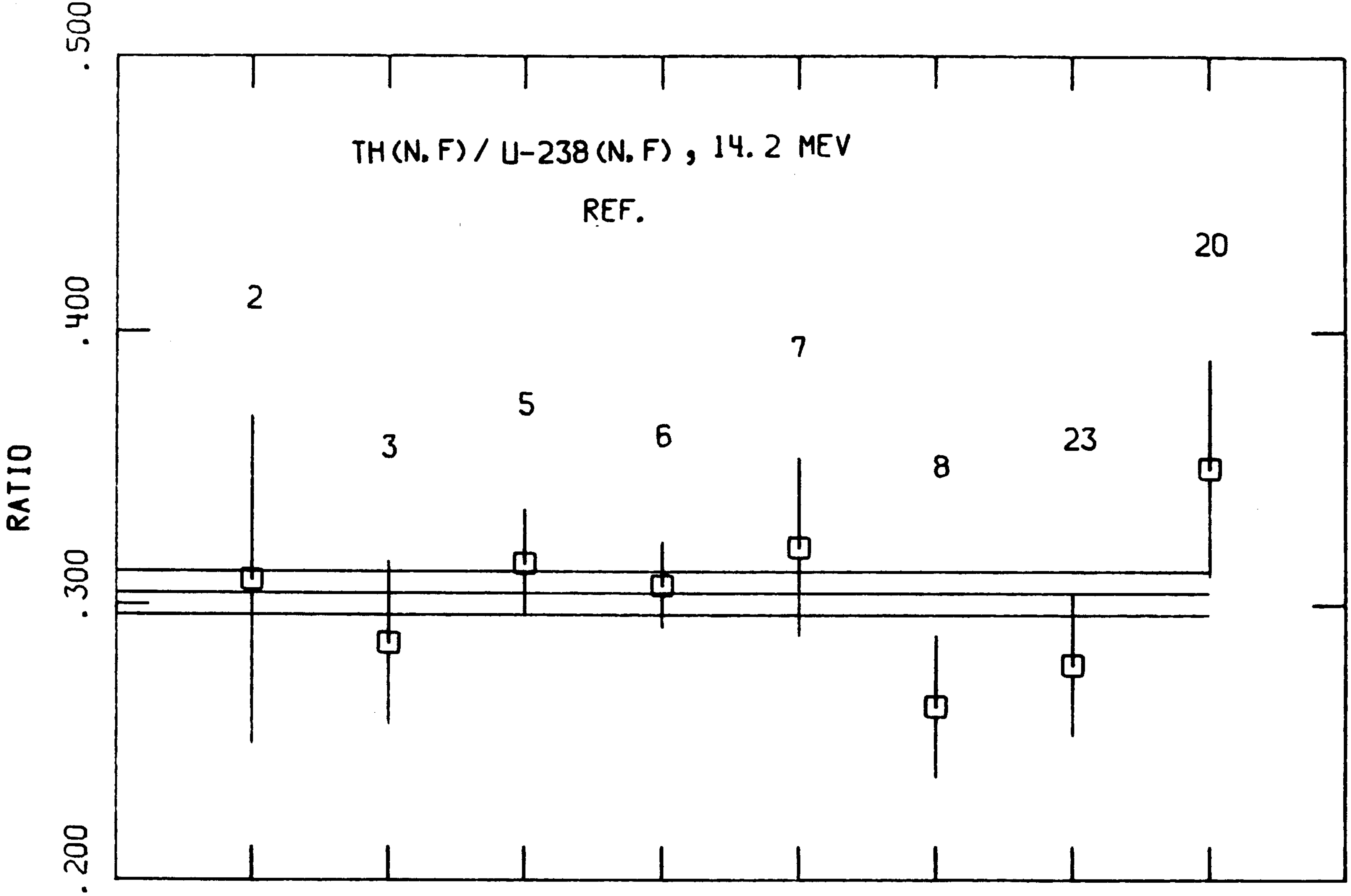
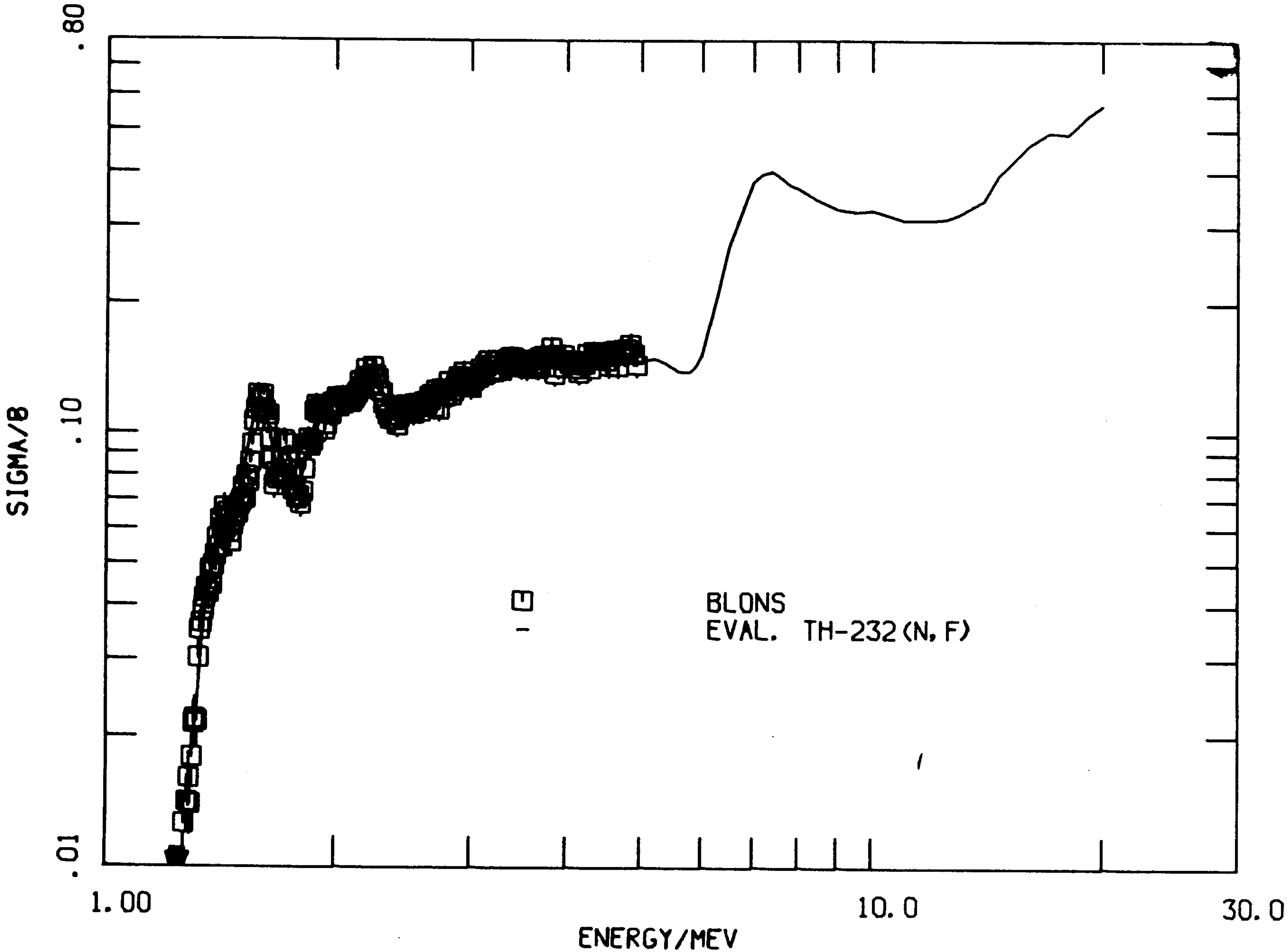
.1500E 02	.4110E 00	.1600E-01
.2000E 02	.5690E 00	.4500E-01



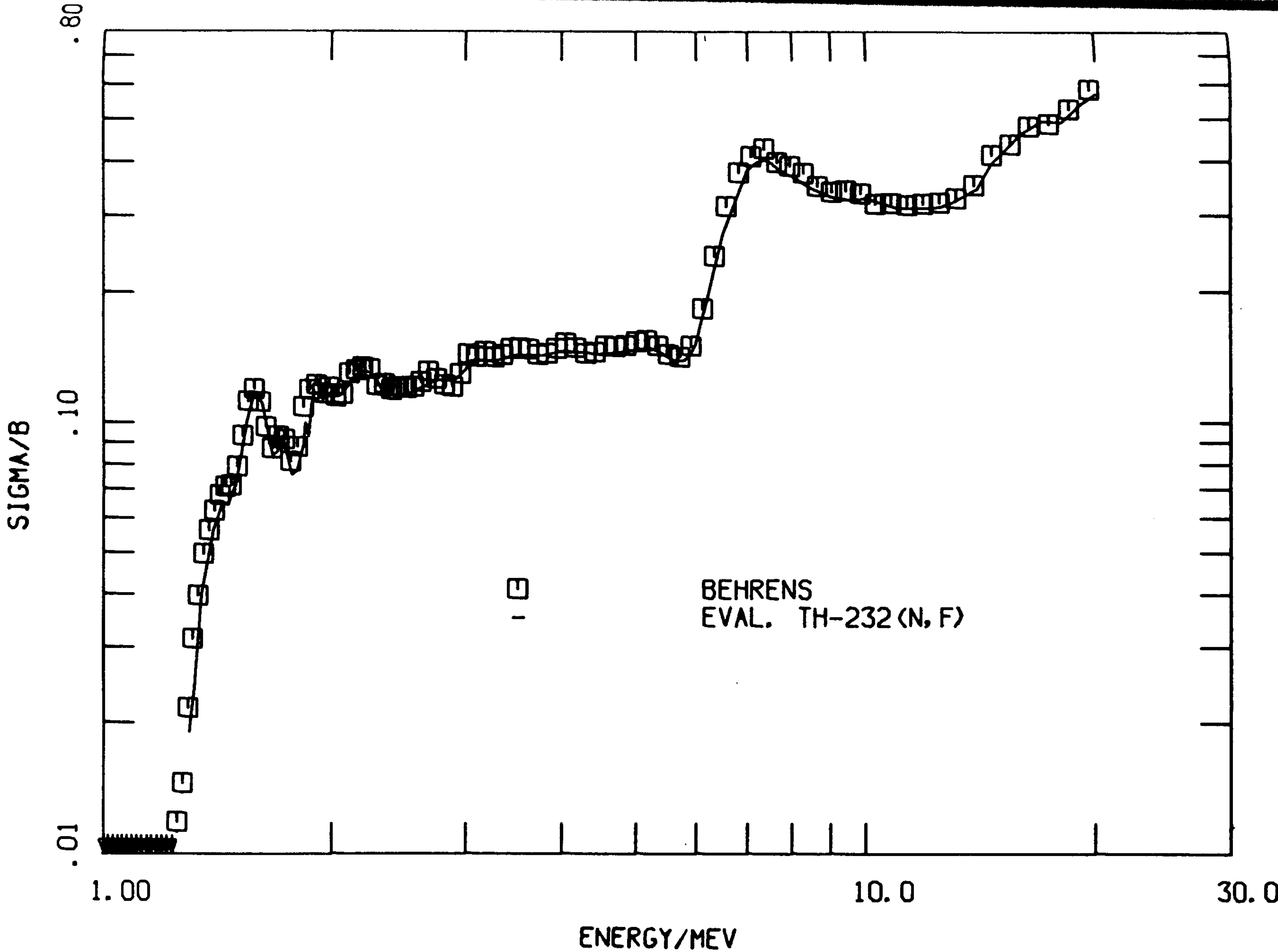
V-1. Comparison of the Present Evaluation with Components Based upon ^{232}Th/^{238}U Ratio, ^{232}Th/^{235}U Ratio and ^{232}Th Absolute Measurements. (ANL-116-77-528).



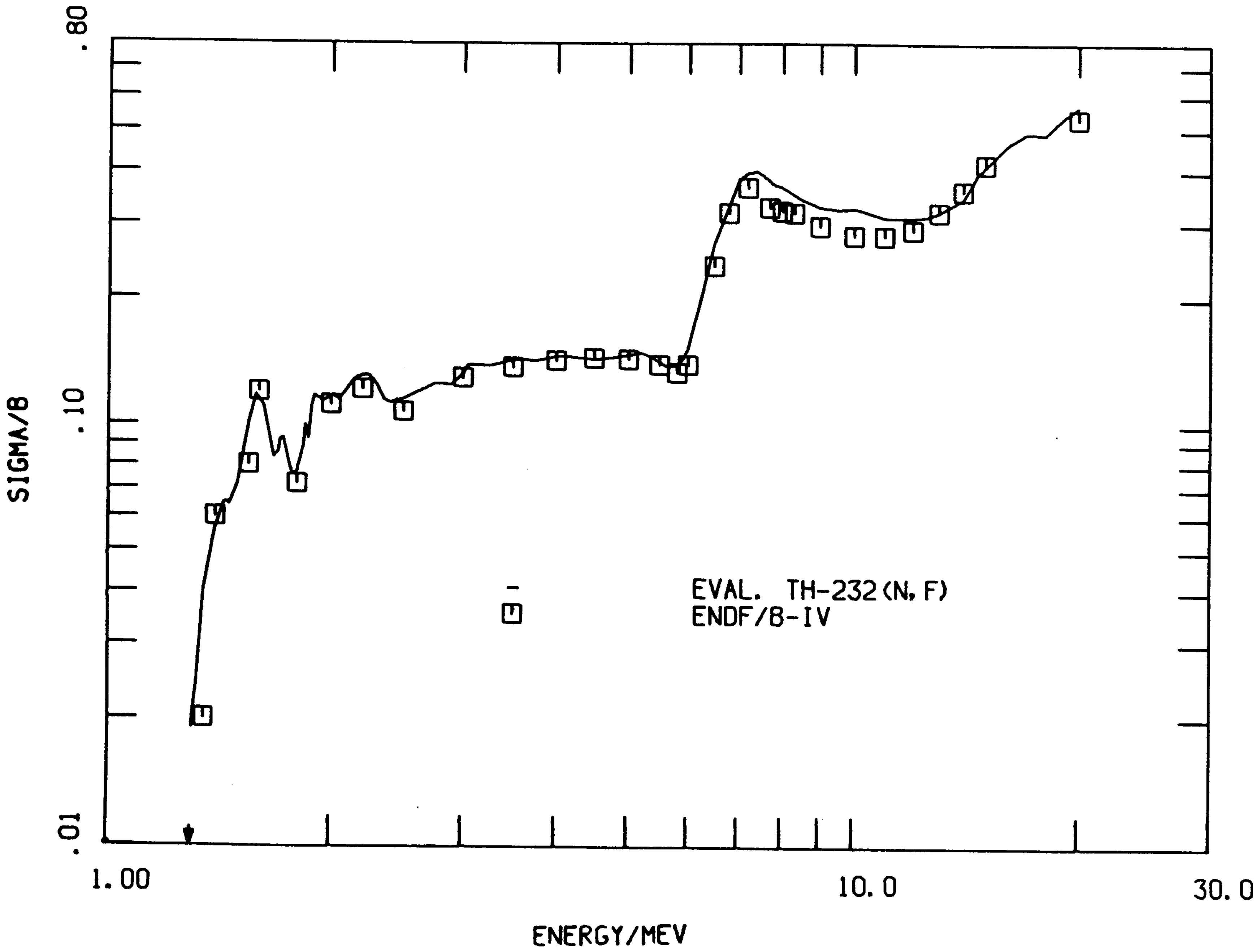
V-2. Comparison of $\sim$14.6 MeV $^{232}Th(n;f)/U^{238}(n;f)$ Ratio Values. Data points are referenced in the text and curves indicate the weighted average ± uncertainty ranges (ANL-116-77-527).



V-3. Comparison of the Present Evaluation with Results Deduced from the Measured Values of Blons et al. (V-16). (ANL-116-77-529).



V-4. Comparison of the Present Evaluation with the Results Deduced from the Measurements of Behrens et al. (V-15). (ANL-116-77-534).



V-5. Comparison of the Present Evaluation with That of ENDF/B-IV. (ANL-116-77-533).

VI. NEUTRON RADIATIVE CAPTURE

Introduction

The data base for the ^{232}Th(n;γ) reaction is very poor. Absolute measurements of this cross section do not exist. Only one measurement relative to H(n;n) exists (VI-1). Three older measurements of the ^{232}Th(n;γ)/^{235}U(n;f) ratio (VI-2, -3, and -4) are in substantial disagreement with a more recent measurement of this quantity (VI-5). The choice of reference cross sections introduces additional problems. The latter are demonstrated with Fig. VI-1 which shows the ^{232}Th(n;γ) cross section measured by Macklin et al. (VI-6) relative to the ^{6}Li(n;α) cross section (the points are the data quoted by Macklin et al.). Renormalization with ^{6}Li(n;α) of ENDF/B-V results in a "resonance" around 250 keV which has no physical justification (Fig. VI-1).

Measurements of the ^{232}Th(n;γ) cross section have a number of features in common with measurements of the ^{238}U(n;γ) cross section. This applies to both prompt γ-ray detection and activation techniques. Thus it appears advantageous to calculate as a first choice ratios of ^{232}Th(n;γ)/^{238}U(n;γ) wherever possible. The disadvantage of this procedure is the rather large uncertainty of the ^{238}U(n;γ) cross section (VI-7). Another ratio which might be derived from measured data is that of ^{232}Th(n;γ)/^{197}Au(n;γ). At higher energies data for ^{232}Th(n;γ)/^{235}U(n;f) exist, and below 50 keV ratios to ^{10}B(n;α) and ^{6}Li(n;α) are available and preferable.

The data base for ^{232}Th(n;γ) is such that rigorous mathematical evaluation techniques as applied for ^{238}U(n;γ) and ^{238}U(n,f) (VI-7) are not applicable at all energies or lead to unsatisfactory results. Guesses have to be made at the present time stressing the need for additional measurements of ^{232}Th(n;γ) cross sections.

$^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ Ratios

Only one direct measurement of this quantity exists but it may be derived from a number of experiments in which $^{232}Th(n;\gamma)$ and $^{238}U(n;\gamma)$ were measured relative to other cross sections. The justification for doing so was given above and further remarks will be added under the following individual sets.

1. Barry et al. (VI-8)

This set of measurements contains the only direct determination of $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ at 600 keV. Otherwise the shape of the cross section curve depends on a Long Counter and the anisotropy of the T(p;n)-reaction. It is not specified in which way the irradiation was carried out, thus the shape curve is of little use.

2. Lindner et al. (VI-5)

This is a repetition of a similar experiment by Miskel, Marsh, Lindner and Nagle (VI-9). $^{235}U(n;f)$ was used as a reference to measure a number of $(n;\gamma)$ cross sections by the activation technique. The ^{235}U-fission chamber was positioned at 0 degrees with respect to a T(p;n) neutron source and the capture samples were irradiated at different angles around the source. Thus, the source anisotropy is another variable and it appears advantageous to eliminate the flux reference from this experiment and to form $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ or $^{232}Th(n;\gamma)/^{197}Au(n;\gamma)$ ratios.

3. Hanna and Rose (VI-1)

$^{238}U(n;\gamma)$ and $^{232}Th(n;\gamma)$ cross sections were measured in this experiment relative to H(n;n). Other data of this type do not exist; therefore, a comparison cannot be made and we prefer to evaluate these data with the other $^{232}Th/^{238}U$ ratio data.

4. Moxon and Chaffey (VI-10)

$^{238}U(n;\gamma)$ and $^{232}Th(n;\gamma)$ were measured in the same experiment. Later a set of revised data was published for $^{238}U(n;\gamma)$ (VI-11) but not for $^{232}Th(n;\gamma)$.

Assuming that $^{232}Th(n;\gamma)$ would be affected similarly to $^{238}U(n;\gamma)$ it appears reasonable to form the $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ ratio from the same experiment. It should be noted that the $^{238}U(n;\gamma)$ data changed in the 30-70 keV range by an average of $\simeq$5 percent (the revised data are higher).

5. Macklin and Gibbons (VI-12)

Data for $^{232}Th(n;\gamma)$ and $^{238}U(n;\gamma)$ were measured relative to $^{181}Ta(n;\gamma)$. Independent absolute values for the latter are not available and thus the ratio $^{232}Th/^{238}U$ was used.

6. Linenberger (VI-2)

Ratios of $^{232}Th(n;\gamma)/^{235}U(n;f)$ and $^{238}U(n;\gamma)/^{235}U(n;f)$ were measured in this experiment and normalized at thermal energies. After renormalization with newer thermal cross sections (VI-13) both, 232Th$(n;\gamma)/^{235}U(n;f)$ and $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ ratios were derived. However, the values in general do not agree with any other data and were ignored in the present calculation.

7. Tolstikov et al. (VI-14)

Only the shapes of $^{232}Th(n;\gamma)$ and $^{238}U(n;\gamma)$ were measured in this experiment and data points are interspaced such as to make these ratios of little value.

The $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ ratio was considered only above 50 keV. Between 50 and 100 keV the data by Moxon and Chaffey (VI-10) agree very well with those of Macklin and Gibbons (VI-12). Other values do not contribute in this energy range. Above 120 keV the data derived from Hanna and Rose (VI-1) are incompatible in shape and normalization with the data derived from Lindner et al. (VI-5). The 600 keV point by Barry et al. agrees within uncertainty limits with Lindner et al. However, the value at 600 keV by Lindner et al. lies at the extreme range of the values and its elimination would suggest a renormalization.

Because the weight of the data by Lindner et al. is substantially higher than that assigned to the data of Barry et al., the ^{232}Th/(n;γ)/^{238}(n;γ) ratio is essentially determined by the former.

^{232}Th(n;γ)/^{197}Au(n;γ) Ratios

The major input comes from a conversion of the data by Macklin et al. (VI-6). These data were originally measured relative to ^{6}Li(n;α). However, utilization of the ENDF/B-V ^{6}Li(n;α) cross section leads to the problem demonstrated in Fig. VI-1. This figure also shows timing problems in the measurements which are related to the flux measurement with a Li(n;α) detector. Forming the ^{232}Th(n;γ)/^{197}Au(n;γ) ratio eliminates the ^{6}Li(n;α) problem but it should be realized that the ^{197}Au(n;γ) cross sections of ENDF/B-V were also strongly influenced by the measurement of Macklin et al.--again relative to ^{6}Li(n;α), and thus the same flux measurement.

Other data for the ^{232}Th(n;γ)/^{197}Au(n;γ) ratio come from the experiment by Miskel et al. (VI-9). These data have much larger uncertainties reflected in a large scatter of individual points. However, the average agrees with the data of Macklin et al. within 2-3 percent. Data by Chelnokov et al. (VI-15) and Lindner et al. (VI-5) were utilized in the evaluation of ^{232}Th(n;γ)/^{10}B(n;α); however, the ^{232}Th(n;γ)/^{197}Au(n;γ) values by Chelnokov et al. are ≃1 percent lower and the values of Lindner et al. are ≃10 percent higher than the evaluated ^{232}Th(n;γ)/^{197}Au(n;γ) ratio.

^{232}Th(n;γ)/^{235}U(n;f) Ratio

Two independent measurements of this ratio were made by Stupegia et al. (VI-3) and Stavisskii et al. (VI-4). Other data (VI-2 and -5) were utilized for the evaluation of the above cited ratios to ^{238}U(n;γ) and ^{197}Au(n;γ). Below 400 keV the data by Stupegia et al. and Stavisskii et al. are in reasonable agreement. Above this energy the data by Stupegia et al. is systematically higher by up to 20 percent. Some preliminary data obtained with a large liquid scintillator tank and by activation techniques relative to $^{235}U(n;f)$ by Poenitz and Smith (VI-18) give substantial support to the data derived from the $^{232}Th(n;\gamma)/^{235}U(n;f)$ ratios.

$^{232}Th(n;\gamma)/^{6}Li(n;\alpha)$ and $^{232}Th(n;\gamma)/^{10}B(n;\alpha)$ Ratios

Below 60 keV the ratio measurement relative to the light element standards were considered. The shape of $Th(n;\gamma)$ was derived from the measurement by Macklin et al. (VI-6) relative to ^{6}Li. Normalization factors were

Macklin et al. (VI-6)	1.00
Yamamuro et al. (VI-16)	1.08
Chelnokov et al. (VI-15)	1.09
Macklin and Lyon (VI-17)	1.04
Moxon and Chaffey (VI-10)	1.02

The value by Moxon and Chaffey is rather uncertain. As mentioned above, $^{238}U(n;\gamma)$ measured in the same experiment was later revised upwards by ≈5 percent. The value by Macklin and Lyon is actually an absolute measurement with a Sb-Be source but has a 20 percent uncertainty.

Evaluated $^{232}Th(n;\gamma)$ Cross Sections

Figure VI-2 shows a comparison of the $^{232}Th(n;\gamma)$ cross sections obtained from the ratios considered above and ENDF/B-V reference cross sections. The results are discrepant by up to 50 percent. A consistent explanation of these discrepancies could not be found. The difference between the data derived from $^{232}Th(n;\gamma)/^{238}U(n;\gamma)$ and that from $^{232}Th(n;\gamma)/^{197}Au(n;\gamma)$ is in the order of 10-15 percent, exceeds estimated uncertainties, and cannot be related to detection techniques applied in the experiments. Below 100 keV the ratio is based on a prompt radiation detection (VI-10 and -12) and above 120 keV on activation techniques (VI-8 and -5). Part of the difference could be due to the reference cross sections.

A ^{232}Th(n;γ) cross section evaluated with previously applied techniques (VI-7) follows closely the values derived relative to ^{238}U(n;γ). Above 2.5 MeV the present evaluation is an arbitrary interpolation between the 2.5 MeV value and a 14 MeV value, both obtained relative to ^{238}U(n;γ). Figure VI-3 shows a comparison with ENDF/B-IV. Figure VI-4 shows a comparison of the more recent data by Macklin et al. (VI-6), by Lindner et al. (VI-5), and preliminary data by Poenitz and Smith (VI-18) with the present evaluation. The latter were not used in the present evaluation. Uncertainties are estimated to be ±10 percent below 1 MeV and ±20 percent above.

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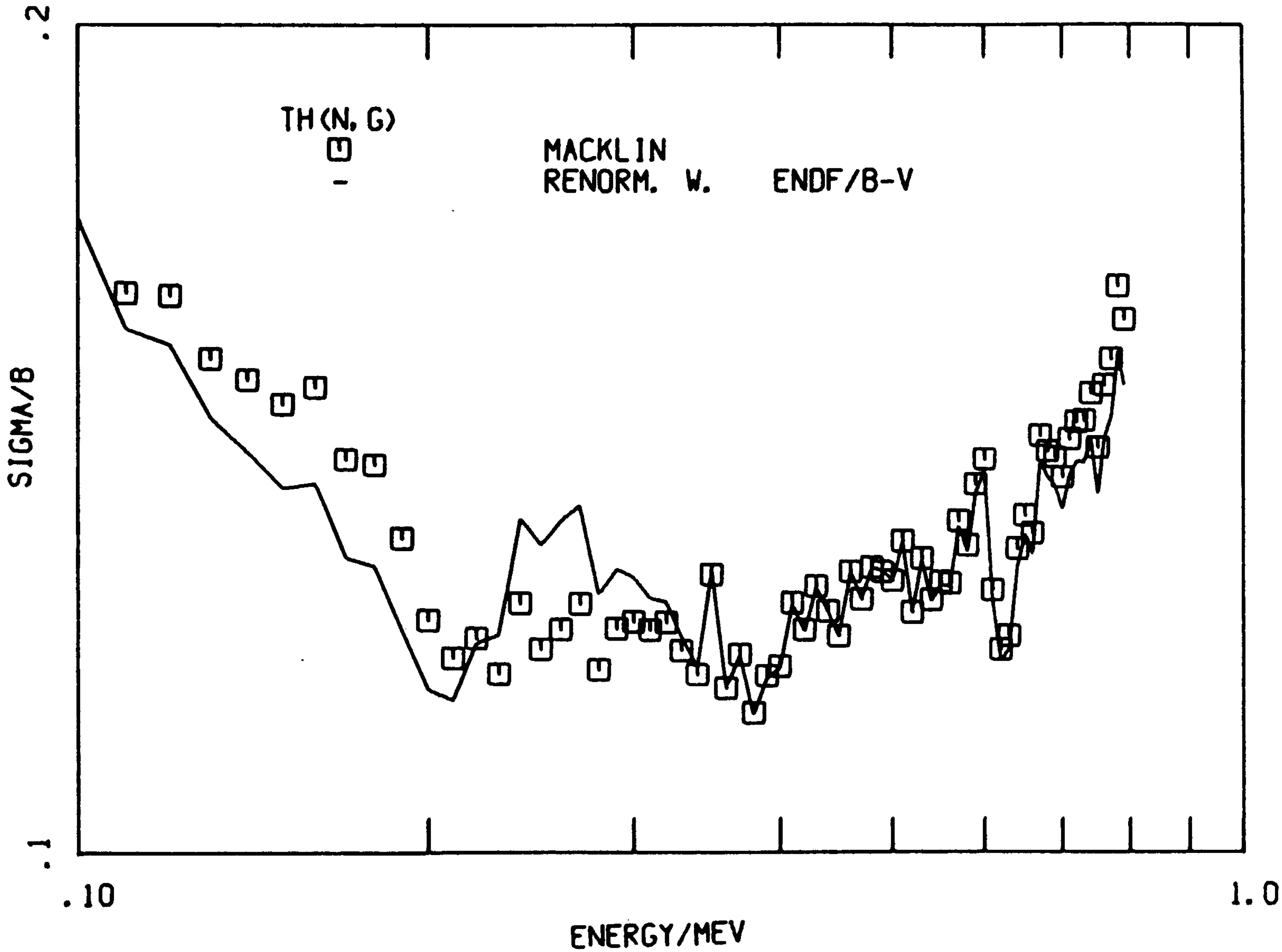
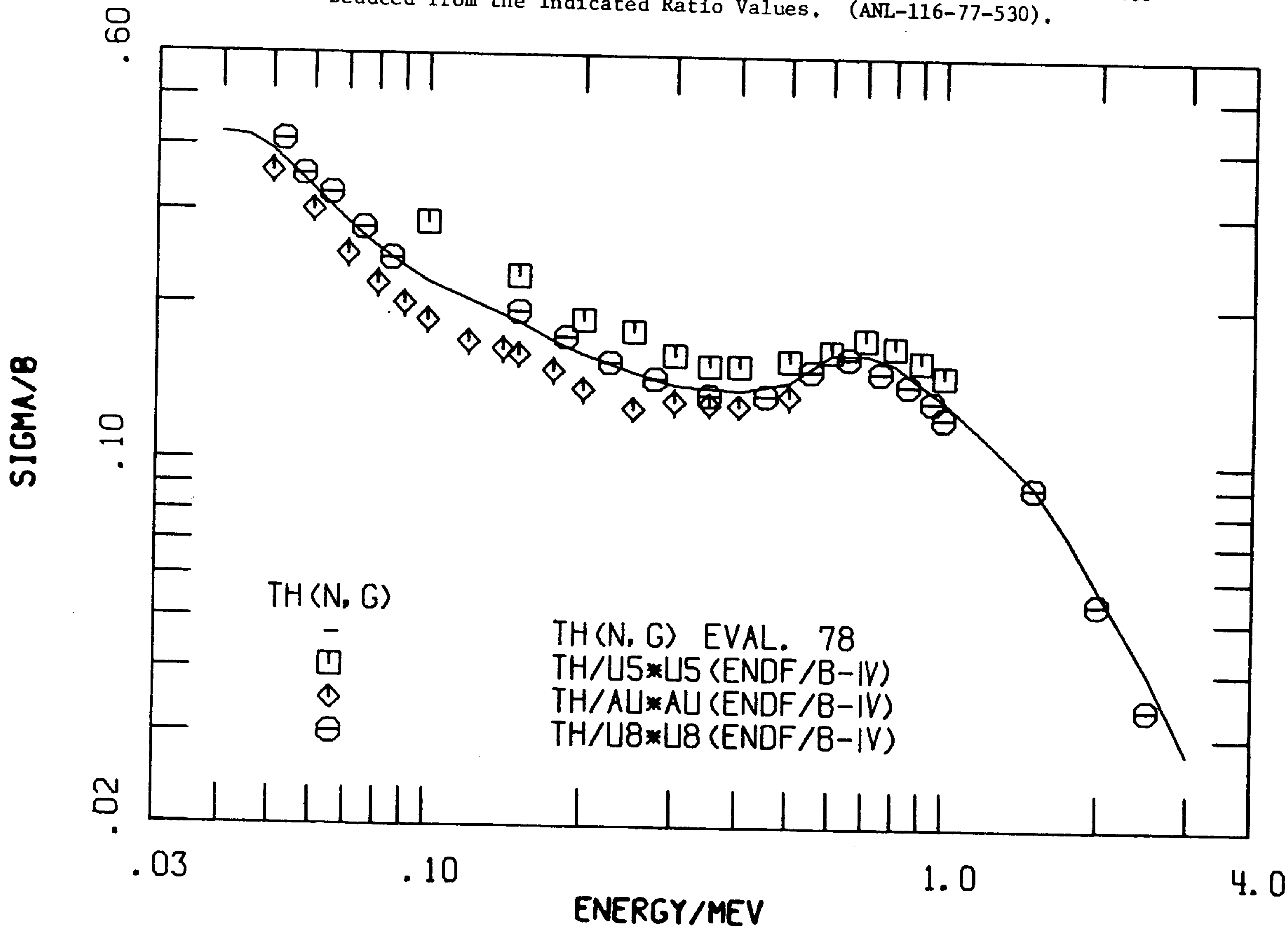
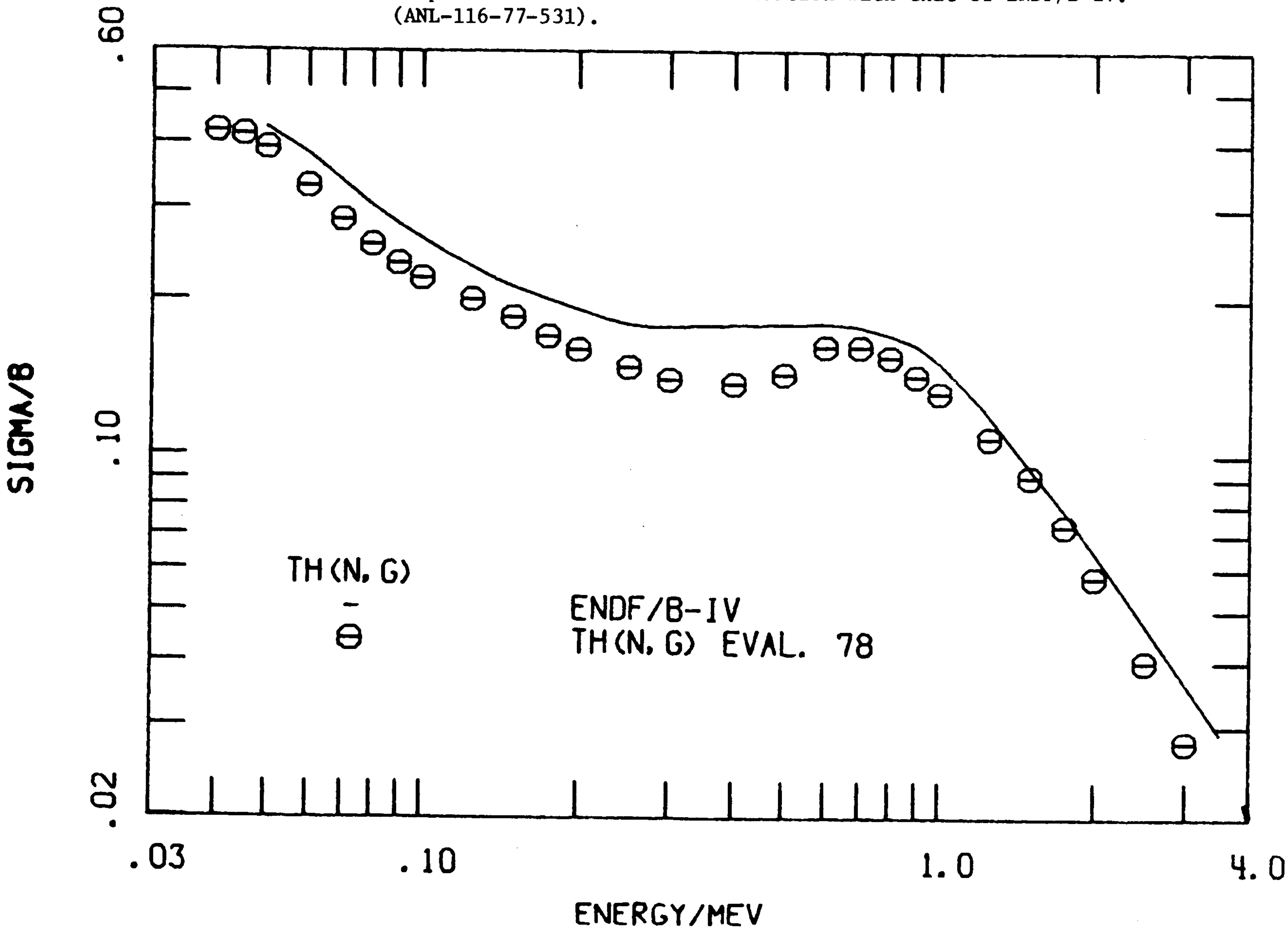


VI-1. Comparison of the Data by Macklin and Halperin with Values Obtained after Renormalization of the Measurements of Macklin and Halperin, (VI-6), with the ENDF/B-V ^{6}Li(n;α) Cross Section (curve). (ANL-116-77-532).

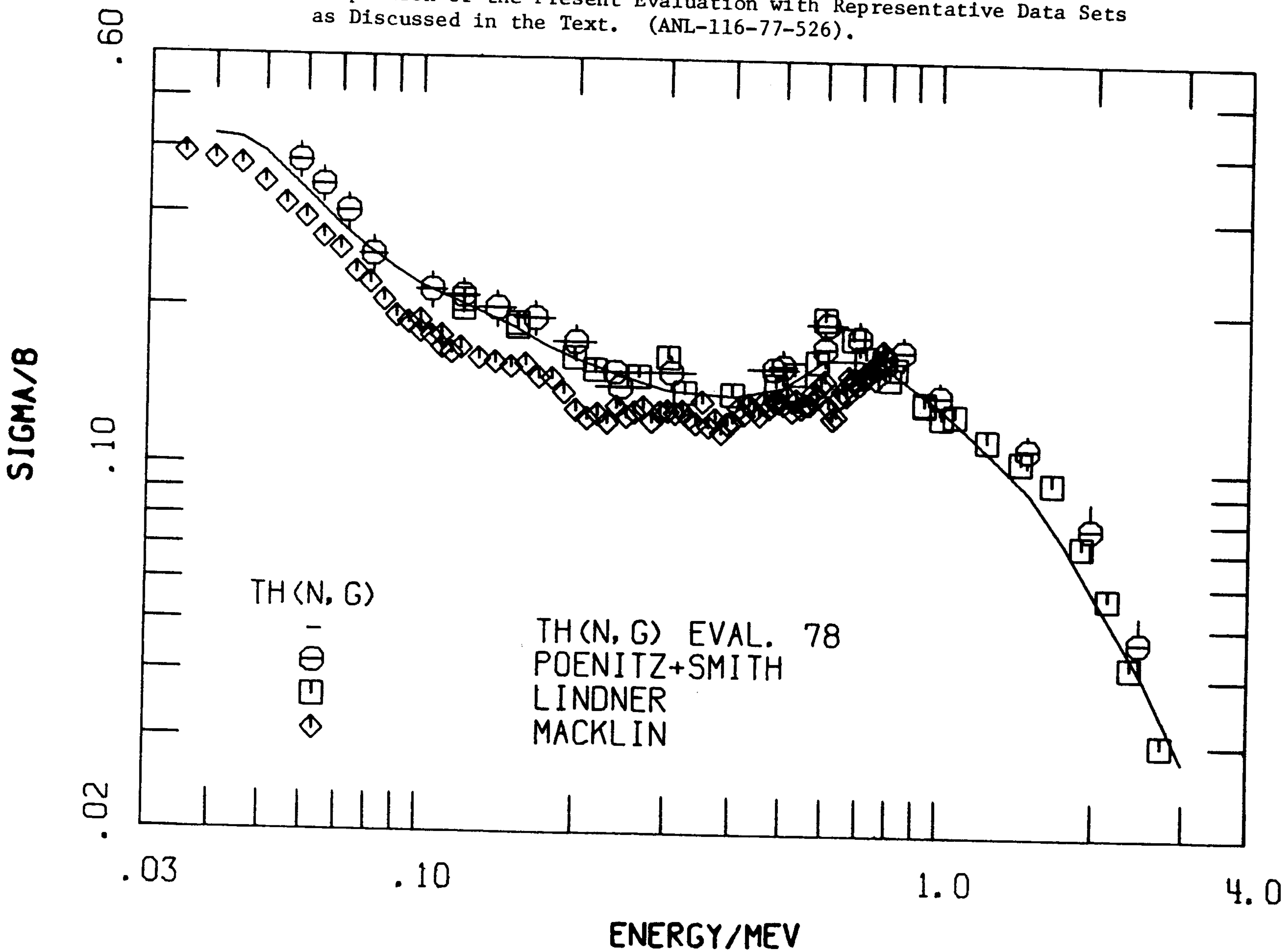
VI-2. Comparison of the Present Evaluation (curve) with Evaluated Results Deduced from the Indicated Ratio Values. (ANL-116-77-530).



VI-3. Comparison of the Present Evaluation with that of ENDF/B-IV. (ANL-116-77-531).



VI-4. Comparison of the Present Evaluation with Representative Data Sets as Discussed in the Text. (ANL-116-77-526).



VII. (n;2n') AND (n;3n') PROCESSES

Although the Q-values of these reactions are negative (Ref. VII-1 and Table VII-1) and thresholds are high enough so that only the high-energy tails of fission neutron spectra are affected. The cross sections for both these reactions rise rapidly above threshold and attain peak values which are substantial.

^{232}Th(n;2n')^{231}Th Reaction

There is a fairly good data base for the (n;2n') reaction from threshold to $\simeq$20 Mev, though none of the differential data is of recent vintage. Some integral data--for ^{235}U fission based spectra--have also been reported. In addition, this reaction has been investigated theoretically during the past several years (e.g., Refs. VII-2 through VII-5). Because of uncertainties introduced by imperfect understanding of the reaction mechanisms, competition from other reaction channels and poor knowledge of level densities and other parameters required for the application of existing theories, the present evaluation is based largely on existing experimental data rather than on computations.

The most extensive data set available is from the work of Butler and Santry (VII-6) who measured the (n;2n') cross section by an activation method involving measurement of ^{231}Th β^- activity. The ^{32}S(n;p)^{32}P reaction was used as a standard in this work. The original results have been renormalized to account for revision of the standard cross section prior to the present evaluation. ENDF/B-IV values (VII-7) were used for the ^{32}S(n;p)^{32}P reference cross section.

The data of Prestwood and Bayhurst (VII-8) are also extensive although they are confined to a more limited energy range (>13 MeV). These authors used a combination of β^- and gamma-ray counting techniques to measure the ^{231}Th activity and relied on ^{238}U fission and the ^{27}Aℓ(n;α) reaction as fluence monitors. There is insufficient data available in their paper to permit renormalization of the cross sections; however, it appears likely that less than 5 percent renormalization would be required to account for changes in the reference cross sections.

The data of Tewes et al. (VII-9) cover a relatively large energy range, but the cross sections carry large error bars. Since the measurements employed a recoil proton detector to measure the neutron fluence, there appeared to be no reason for renormalization of the data.

The single data point of Perkin and Coleman (VII-10) at 14.1 MeV is of considerable interest for this evaluation because of the apparently accurate methods used in the measurement. The neutron fluence was determined absolutely by the detection of the associated α particles from the T(d;n)α neutron-source reaction. Low-energy gamma rays from ^{231}Th decay were detected with a sodium iodide scintillation detector which had been calibrated by observing the identical spectrum originating from the α-particle decay of ^{235}U to ^{231}Th. The mass of uranium was determined very accurately and the concentration of the daughter ^{231}Th was in equilibrium with the ^{235}U present in the calibration standard.

Zysin et al. (VII-11) measured the ratio of the (n;2n') and fission cross sections for ^{232}Th at 14.7 MeV. This involved detection of activity of ^{231}Th as well as the activities of ^{99}Mo and ^{140}Ba produced by the fission process. Consequently, determination of the (n;2n') cross section required knowledge of not only the fission cross section, but also of the mass yields and decay properties for the Mo and Ba fragments. Reference VII-11 does not provide sufficient information to permit a thorough investigation of normalization effects; however, the results were partially renormalized to account for the known change in the fission cross section (as reflected in ENDF/B-IV).

Because of the uncertainties involved in this cross section value, it was not given serious consideration in the evaluation.

Halperin et al. reported three cross section values for the $^{232}Th(n;2n')$ reaction in a progress report (VII-12); however, no detailed information on these experiments is available. Similarly, Cochrane et al. (VII-13) report (n;2n') cross section values with no documentation of their experimental procedure.

Batchelor et al. deduced a value for the (n;2n') cross section at 7 MeV from time-of-flight measurements on the neutron emission spectrum from thorium (VII-14). Because of the interference of several other processes, this value must be assumed to be very uncertain.

Phillips (VII-15) performed a measurement at 15 MeV using the same approach as described in the later work documented in Ref. VII-10 for calibrating his proportional-counter gamma-ray detector. Because of the uncertainty associated with neutron fluence measurement using the $^{32}S(n;p)^{32}P$ reaction, this point is accorded less weight in the evaluation than the more recent work of Perkin et al. (Ref. VII-10).

In addition, it is worthwhile mentioning the result of an evaluation of 14.7 MeV data by Body and Csikai (VII-16). Their analysis of the experimental data as of 1973 yielded the cross section value 1.156 barns. Statistical model calculations by Pearlstein (VII-4) yielded values at 13.1, 14.1 and 15.1 MeV.

The present evaluation differs little from ENDF/B-IV (VII-7) below 8 MeV. In this region, the cross section is defined by the data of Butler and Santry (VII-6); their results are confirmed by the work of Batchelor et al. (VII-14), Cochrane et al. (VII-13) and Halperin et al. (VII-12) at 7 MeV and by the data of Cochrane et al. (VII-13) and Halperin et al. (VII-12) at $\simeq$8 MeV. In the range 8-12 MeV, the present evaluation predicts somewhat lower cross sections than ENDF/B-IV since it tends to follow the data of Butler and Santry (VII-6). In the range 13-15 MeV, the present evaluation yields cross sections which are systematically lower (by ≃10%) than ENDF/B-IV (Ref. VII-7). The lowering of the cross section in this region results from attaching greater weight to the data of Butler and Santry (VII-6) and Perkin and Coleman (VII-10) than to the results of Prestwood and Bayhurst (VII-8). The 14.7-MeV evaluated value of Body and Csikai also influenced the present evaluation considerably in this region. The calculated values of Pearlstein (VII-4) appear too small and were disregarded. From 15-20 MeV, the present evaluation is a smooth curve drawn through the few available data points. The present evaluation predicts much lower cross sections above 15 MeV than ENDF/B-IV (VII-7). This large difference should have little effect on fission reactor applications. Table VII-2 gives the estimated uncertainties for the present evaluation.

Although this information had no influence on the present differential evaluation, it is of interest to examine the ^{235}U fission-spectrum-average cross section values for the $^{232}Th(n;2n')^{231}Th$ reaction which are available from the literature. These values are listed in Table VII-3. The value calculated using the present evaluation is more or less consistent with other available results.

$^{232}Th(n;3n')^{230}Th$ Reaction

^{230}Th is relatively long-lived, so this reaction cannot be easily examined by the activation method. There is only one experimental point at 14 MeV from the work of McTaggart and Goodfellow (VII-23). Their value of 0.85 barn was deduced indirectly from a thin spherical-shell-transmission study of inelastic processes. Consequently, the cross section is very sensitive to precise knowledge of $\bar{s}$, σ_{nf}, σ_{non-el} and $\sigma_{n,2n}$. If values of these parameters are taken from the present evaluation, the 14-MeV cross section deduced from their measurement is 0.52 barn. This latter value was used in the evaluation. The systematics of (n;3n') cross sections can be estimated from theoretical work (e.g. Refs. VII-4, VII-24 and VII-2).

The above data base gives little guidance to the evaluation above 15 MeV. Thus primary reliance was placed upon the nonelastic cross section and the other and better known partial cross sections. The difference yielded the present evaluation which is reasonably consistent with the single measured value of Ref. VII-23. The present evaluation differs from that of ENDF/B-IV but both are relatively uncertain and thus the differences between the two evaluations may not be significant.

Energy-angle Dependence of the Emitted Neutrons

The angular and energy dependence of neutrons emitted from the (n;2n') and the (n;3n') processes were determined using the statistical model of Segev et al. (VII-24) with the addition of a "hard" precompound component. This model alone is based upon the compound-nucleus reaction and does not include precompound processes that will lead to angular isotropies and increased high-energy neutron emission. This file assumes isotropic emission and tabulates spectral energy distributions calculated as outlined above. The simple approximation of isotropy will probably have little impact on most applications of the data and there is really little alternative as the accepted ENDF formats preclude the definition of angle-energy correlations of continuum emission spectra.

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TABLE VII-1. Q-Values and Thresholds for the Thorium (n;2n') and (n;3n') Reactions

Reaction	Q-Value (MeV)	Threshold (MeV)
$^{232}Th(n;2n')^{231}Th$	-6.4340[a]	6.4620
$^{232}Th(n;3n')^{230}Th$	-11.563[a]	11.613

[a]Computed from mass excess tables in Ref. VII-1.

TABLE VII-2. Estimated Uncertainties in the Present Evaluation of the (n;2n') Cross Section

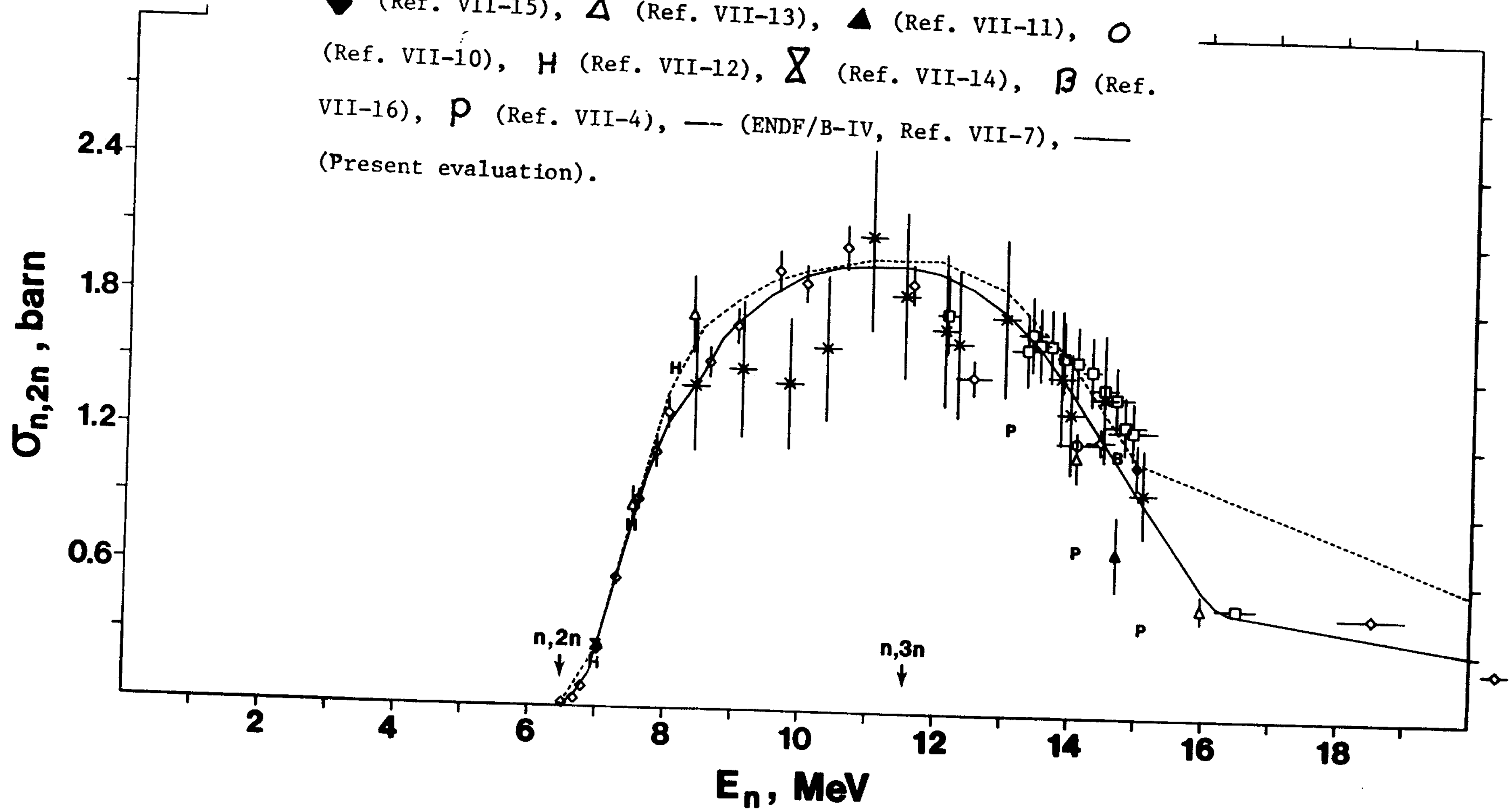
Energy Range (MeV)	Uncertainty (%)
<8 MeV	∿15%
8-13 MeV	∿10%
13-15 MeV	∿15%
>15 MeV	∿20%

TABLE VII-3. Spectrum-Average Cross Sections for the $^{232}Th(n;2n')^{231}Th$ Reaction in ^{235}U Fission Neutron Spectra

Author(s)	$\bar{\sigma}$ (millibarn)	Type
Phillips (1958)[a]	12.4 ± 0.6[b] 16.2 ± 0.7[c]	Expt.
Kobayashi et al. (1971)[d]	12.5 ± 0.84	Expt.
Schuman et al. (1969)[e]	∿10	Expt.
Pearlstein (1961)[f]	16	Theo.
Calamand (1974)[g]	14.2 ± 1.1	Eval.
ENDF/B-IV (1975)[h]	17.9[i]	Eval.
Present Evaluation	16.7[i]	Eval.

[a] Ref. VII-17.
[b] Original value reported in Ref. VII-17.
[c] Renormalized value corresponding to recent value from Fabay et al. (Ref. VII-18) for the $^{32}S(n;p)^{32}P$ standard cross section.
[d] Ref. VII-19.
[e] Ref. VII-20.
[f] Ref. VII-4.
[g] Ref. VII-21.
[h] Ref. VII-7.
[i] Spectrum-average cross section computed using evaluated differential cross sections and the Maxwellian fission spectrum for ^{235}U fission from Ref. VII-22.

VII-1. Comparison of cross section values for the $^{232}Th(n;2n)^{231}Th$ reaction: X (Ref. VII-9), □ (Ref. VII-8), ◇ (Ref. VII-6), ◆ (Ref. VII-15), Δ (Ref. VII-13), ▲ (Ref. VII-11), O (Ref. VII-10), H (Ref. VII-12), ⧗ (Ref. VII-14), β (Ref. VII-16), P (Ref. VII-4), --- (ENDF/B-IV, Ref. VII-7), —— (Present evaluation).



VIII. DELAYED FISSION NEUTRON EMISSION

This section reviews the current status of delayed neutron data for ^{232}Th and defines the relevant evaluated data file. Since it is directed toward utilization in reactor calculations, emphasis is placed on group parameters, total yield, dependence of the yield on energy and the equilibrium energy spectrum. Although it has been accumulating for over a quarter of a century, the data base for ^{232}Th delayed neutrons is limited. A reviewer receives the impression that the accuracy of some of the measurements is doubtful and the quality of the reporting of some experiments is so poor that an estimate of their reliability cannot be made. The only recent work has concerned the delayed-neutron energy spectrum. There is virtually no information on the energy dependence of the total yield. Several valuable reviews concerning the general subject of delayed neutrons are listed in Refs. VIII-1 through -6.

A. Group Parameters

Delayed neutrons occur when beta decay in fission-product-mass chains leads to nuclei which are unstable to neutron emission. A large number of these precursors have now been identified but it appears that, for applications, the time dependence of the delayed neutron emission can be represented by six precursor groups with a single decay constant assigned to each group. The work described in Ref. VIII-7 showed that six groups provided a better fit to the data than either 5 or 7 and that the group decay constants were remarkably insensitive to the fissioning nucleus. Measurements of the group constants for ^{232}Th are also described in Refs. VIII-8 and IV-9; however, these essentially confirm the results of Ref. VIII-7.

The use of six groups is a practical and empirical matter and, since the number of precursors is much larger, the parameters derived from a data set may depend on the fitting procedure used. The reported parameters are a self-contained set. Combinations of independent measurements should be based on the original data but not on the derived parameters.

The recommended group parameters are taken from Ref. VIII-7 and are listed in Table VIII-1.

B. Total Yield

The delayed neutron yield measurements are listed in Table VIII-2. The data was treated as follows:

1. Some measurements did not include the shorter lived groups. In these cases the yield was corrected for the missing groups using the relative group yields in Table VIII-1.

2. Some measurements were made relative to the ^{235}U delayed neutron yield. These were converted to delayed neutrons/fission or renormalized using the evaluated delayed neutron yield given in Ref. VIII-5. (Y(U-235) = 0.1668 ± 0.00070).

3. All errors were converted to standard deviations. If the form of the error was not specified, it was assumed to be a standard deviation.

It has been shown in Ref. VIII-23 that, in general, the delayed neutron yield is independent of energy below the (n;n',f) threshold. The data in Table VIII-2 and Ref. VIII-24 suggest that this is also true for ^{232}Th so all the data below $\gtrsim$4 MeV were combined. A weighted average was taken of the relative values and the error in the ^{235}U delayed neutron yield was folded in. A weighted average of the absolute measurements and this value is given in Table VIII-3 and compared with recent evaluations.

All other yield measurements were made in the vicinity of 14 MeV. The high-energy yield values obtained prior to 1966 are larger than the low-energy yield while those obtained after 1966 are smaller. There is good reason to believe that the delayed neutron yields decrease with increasing energy (see Section VIII-C) so the pre-1966 data were rejected. The data of Ref. VIII-21 appears to be preliminary results of the work reported in Ref. VIII-22 so the earlier values were rejected. Thus there are three measurements at 14 MeV (or 14.1) and two at 14.9 MeV. Since the energy dependence in this region is unknown, they were treated separately. Weighted averages are given in Table VIII-3.

C. Energy Dependence

The energy dependence of the ^{232}Th delayed-neutron yield is not defined by existing experimental data; however, procedures for estimating the energy dependence are discussed in Ref. VIII-6 and VIII-25. The procedure described in Ref. VIII-6 should be particularly applicable in the special case of ^{232}Th.

As long as the fissioning nucleus has mass A_c, the delayed neutron yield is assumed to be independent of the excitation energy. If a neutron is emitted first, the fissioning nucleus then has mass A_c-1 and the delayed neutron yield will change due to the change in the mass yields. This corresponds very well to the measurements on uranium and plutonium isotopes in Ref. VIII-23. The energy dependent delayed neutron yield can be written as

$$Y(A_c,E) = \frac{1}{\sigma_f}\,\sigma(n,f)Y(A_c) + \sigma(n,n'g)Y(A_c-1) + \sigma(n,2n'f)Y(A_c-2) + \ldots \qquad \text{(VIII-1)}$$

where σ_f, $\sigma(n,f)$, etc. are energy dependent total and partial fission cross sections and $Y(A)_c$ in the yield for compound nucleus A_c at low excitation energies.

The partial fission cross sections are not known but some estimate can be made from the shape of σ_f. It is often assumed that $\sigma(n,f)$ is independent of energy since there is evidence that the ratio of the neutron to fission widths are only weakly energy dependent (Ref. VIII-26). However the shape of σ_f suggests that for ^{232}Th the ratio decreases with increasing energy. The partial fission cross sections that were used are shown in Fig. VIII-1. These are adjusted to obtain agreement with the 14.9 MeV value of the delayed neutron yield.

The value used for Y at A_c equal 233 was taken from Table VIII-3. The other values were estimated from an empirical correlation between the delayed neutronyield and the mass and charge of the fissioning nucleus.

$$Y = [\exp 14.638 + 0.1832 (A_c - 3Z) A_c/Z] \quad \text{(VIII-2)}$$

The values of the constants were taken from Ref. VIII-6 where a fit was made to all available delayed neutron data. The uncertainty in Y is ±11.3%. The energy dependent yield as calculated by Eq. VIII-1 is shown in Fig. VIII-1.

D. Energy Spectrum

There are very few measurements of the ^{232}Th delayed neutron energy spectrum. In Ref. VIII-27, group and equilibrium spectra are constructed from the individual spectra of 20 of the major delayed neutron precursors and the ^{232}Th mass yield distribution. The precursor spectra were measured with an ^{3}He detector as described in Refs. VIII-28 through VIII-30. In spite of the limited number of precursors, the constructed spectra for several uranium and plutonium isotopes agree very well with measured spectra, particularly at higher energies. Unfortunately ^{3}He proportional counters are unreliable below 0.1-0.2 MeV so the low energy portions of these spectra may not be reliable.

Ref. VIII-30 describes a measurement of the equilibrium spectrum using a proton recoil detector. The energy range was 0.02-1.5 MeV and $\simeq$20 percent of the total delayed neutrons were found to have energies <0.1 MeV. This finding is supported by a measurement of the spectra of $^{87}Br + ^{88}Br$ where nearly half lies below 0.1 MeV (Ref. VIII-32).

It is recommended that the data of Ref. VIII-31 be used for the equilibrium spectrum. No group spectra are recommended at this time because of the lack of information below ~0.1 MeV. Instead, the equilibrium spectrum is assigned to all groups. This may introduce some error in time-dependent calculations as Ref. VIII-27 shows considerable difference in the higher energy parts of the group spectra.

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TABLE VIII-1. Recommended Group Parameter for ^{232}Th

Group	Fractional Group Yield	$t_{1/2}$ (sec)
1	0.034 ± 0.003	55.9 ± 1.30
2	0.150 ± 0.007	20.8 ± 1.00
3	0.155 ± 0.031	5.73 ± 0.33
4	0.446 ± 0.022	2.16 ± 0.11
5	0.172 ± 0.019	0.57 ± 0.06
6	0.043 ± 0.009	0.21 ± 0.03

TABLE VIII-2. ^{232}Th Delayed Neutron Yield Data

Ref.	Ref. No.	Reported	Adjusted	Energy MeV	Neutron Source	Type
Sun et al. (1950)	VIII-10	0.08 ± .03	0.08 ± .03	14 Max	D + ^{12}C	abs.
Brunson (1955)	VIII-11	3.09 ± .52 × Y_{th}(U-235)	0.0547 ± .0138	3.0	EBR-I	rel.
Rose, Smith (1957)	VIII-12	0.038 ± .008	0.0396 ± .0083	3.0	ZEPHYR	abs.
Rose, Smith (1957)	VIII-12	2.21 ± 0.27 × Y_f(U-235)	0.0375 ± .0047	3.0	ZEPHYR	rel.
Keepin et al.[a] (1957) Evans et al. (1972)	VIII-7 VIII-13	0.0505 ± .0030	0.0505 ± .0030	3.5	GODIVA	abs.
Maksyutenko (1959)	VIII-14	3.40 ± .28 × Y_{th}(U-235)	0.0567 ± .0047	2.4	D+D	rel.
		3.18 ± .26 × Y(U-235)	0.0530 ± .0043	3.3	D+D	rel.
		5.11 ± .38 × Y_{th}(U-235)	0.0852 ± .0063	15.0	D+T	rel.
McGarry et al. (1960)	VIII-15	0.058 ± .014	0.58 ± .014	14.0	D+T	abs.
Shpakov et al. (1961)	VIII-16	0.075 ± .007	0.0782 ± .0075	14.5	D+T	abs.
Masters et al.[b] (1969)	VIII-17	0.057 ± .005	0.057 ± .005	3.1	D+D	abs.
Evans et al. (1973)	VIII-18	0.030 ± .002	0.030 ± .002	14.9	D+T	abs.
Keepin (1969)	VIII-19	1.19 ± 0.14 1.23 ± 0.11	0.0311 ± .0038	14.1	D+T	abs.

Ref.	Ref. No.	Reported	Adjusted	Energy MeV	Neutron Source	Type
Notea (1969)	VIII-20	$0.77 \pm 0.30 \times Y_{th}$(U-235)	0.0131 ± .0053	14.0	D+T	rel.
Herrmann (1969)	VIII-21	0.0190 ± .0050	0.0202 ± .0025	14.0	D+T	rel.
Benedict (1970)	VIII-22	0.0191 ± .0065	0.0203 ± .0033	14.0	D+T	rel.

[a] These results were revised in Ref. VIII-13. The revised values are reported.

[b] These results were revised in Ref. VIII-18. The revised values are reported.

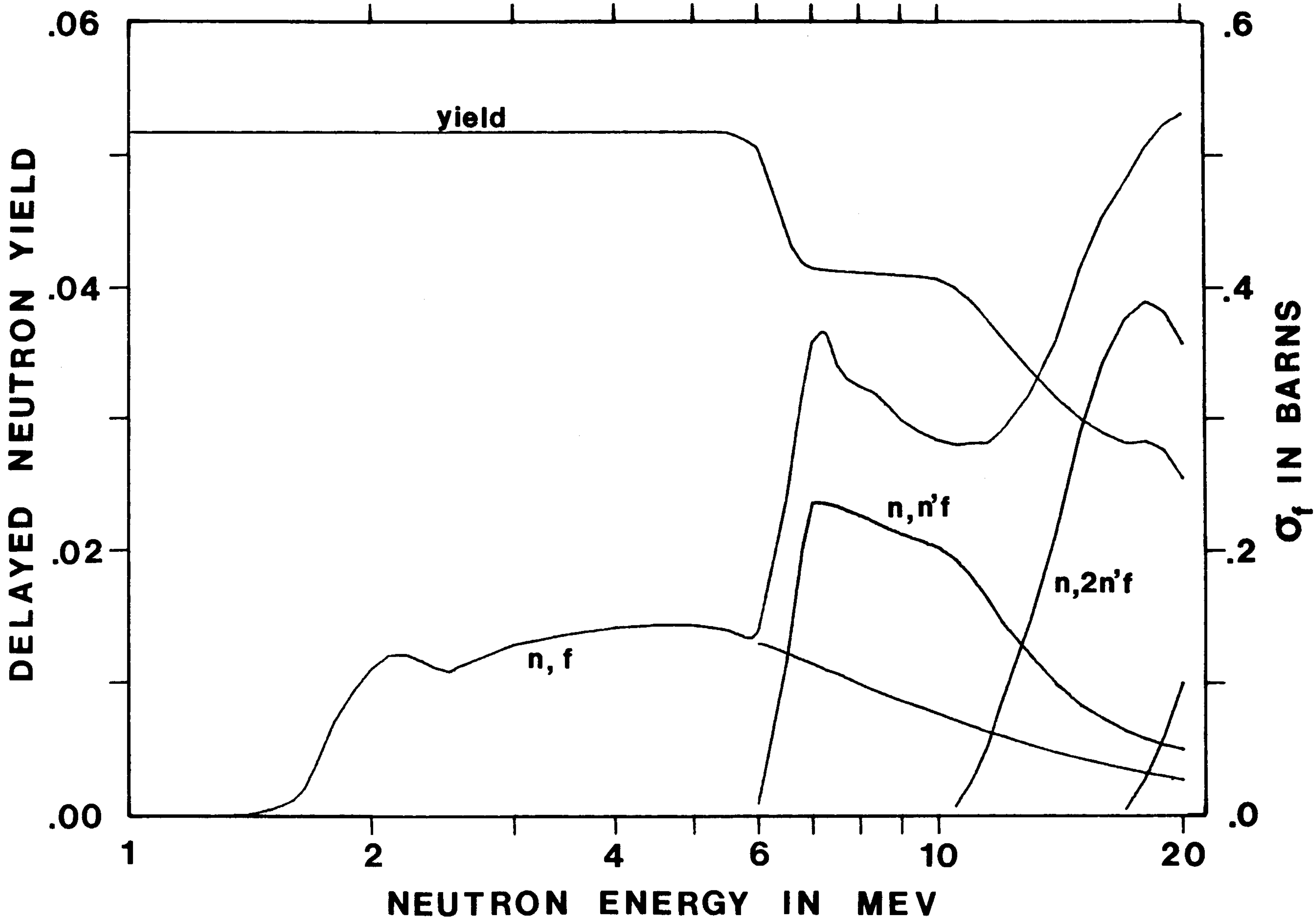
TABLE VIII-3. Evaluated Total Yields of ^{232}Th Delayed Neutrons

Source	E_n (MeV)	Yield n/f	Error
This Evaluation	<4	0.0518	0.0020
	14.1	0.0265	0.0026
	14.7	0.0296	0.0016
Ref. VIII-5	<4	0.0527	0.0040
Ref. VIII-6	<4	0.0545	0.0011

TABLE VIII-4. The Normalized Equilibrium Delayed Neutron Spectrum for ^{232}Th

E_n (keV)	N(E)	E_n (keV)	N(E)
28.50	0.0	170.0	21.39×10^{-4}
34.16	12.32×10^{-4}	238.0	11.51×10^{-4}
40.79	37.61×10^{-4}	257.0	11.38×10^{-4}
42.02	37.76×10^{-4}	301.0	7.063×10^{-4}
49.80	24.59×10^{-4}	338.0	7.979×10^{-4}
55.50	30.35×10^{-4}	415.0	9.026×10^{-4}
61.00	23.22×10^{-4}	520.0	6.736×10^{-4}
72.50	33.36×10^{-4}	549.0	6.606×10^{-4}
84.50	26.55×10^{-4}	615.0	4.644×10^{-4}
98.70	26.68×10^{-4}	910.0	2.354×10^{-4}
111.5	20.93×10^{-4}	1360	$.8448 \times 10^{-4}$
127.7	25.57×10^{-4}	3000	0.0
155.0	20.86×10^{-4}		

VIII-1. Total Delayed Neutron Yield and Partial Fission Cross Sections of ^{232}Th. Curves indicate values from the present evaluation.



IX. PROMPT FISSION NEUTRON EMISSION

A. Introduction

The data base for defining the number per fission and energy spectrum of the prompt fission neutrons from ^{232}Th fission is very poor. There are several sets of $\bar{\nu}_p$ measurements below 4 MeV and another group near 14 MeV although the agreement of the latter data is poor. There is only a single measurement of the energy spectrum and this is at 14 MeV. Consequently, the recommendations in this section rely heavily on theory and systematics.

B. $\bar{\nu}_p$

The knowledge of $\bar{\nu}_p$, the number of prompt neutron per fission, for ^{232}Th and its energy dependence is based on a few measurements. Most of the work was done in the 1960's. There have been no recent measurements. Reviews by Davey in 1971 (IX-1) and Fillmore in 1968 (IX-2) included virtually all the data that is presently available.

The experimental data are taken from Refs. IX-3 through IX-11. Since these are all relative measurements, and were made over an extended period of time, it was necessary to reduce all the experimental values to a common normalization. Most of the data are based on $\bar{\nu}_p$ for ^{235}U thermal fission or for ^{252}Cf spontaneous fission. The values used for renormalization were taken from a recent evaluation by Lemmel (IX-12). They are:

^{252}Cf(spon.) $\bar{\nu}_p = 3.737 \pm 0.008$,

^{235}U(thermal) $\bar{\nu}_p = 2.400 \pm 0.005$.

The renormalized data are listed in Table IX-1.

One data set (IX-11) was normalized to $\bar{\nu}_p$ for ^{235}U fission at 0.37 MeV. Unfortunately the measurements of $\bar{\nu}_p$ for ^{235}U in this region show considerable scatter and appear to be high when compared to data below 0.1 MeV and above 0.5 MeV (IX-1). The normalization value was taken from an evaluation by Mather and Bampton (IX-13) which takes the departure from linearity into account. After correcting for the change in $\bar{\nu}_p$ of ^{252}Cf the ^{235}U (0.37 MeV) $\bar{\nu}_p$ = 2.459. The measurements described in Refs. IX-4 and IX-8 were made relative to ^{238}U at 1.4 and ^{235}U at 14.3 MeV respectively. They were normalized to values which were taken from Davey's evaluation (IX-1) and corrected to the above $\bar{\nu}_p$ for ^{252}Cf spontaneous fission giving ^{238}U (1.4 MeV) = 2.441 and ^{235}U (14.3 MeV) = 4.406.

The measurement by Johnstone (IX-3) was based on the rate of emission of spontaneous fission neutrons from uranium as measured by Littler (IX-14). That, in turn, was based on a calibrated Ra-Be neutron source, so no renormalization was required.

A new set of measurements of the ratio of $\bar{\nu}_p$ for ^{232}Th to $\bar{\nu}_p$ for ^{235}U by Howe and Browne of Lawrence Livermore Laboratory will be completed by late 1977. These ratios will be determined for the energy range from threshold to 20 MeV. Hopefully, the questions of apparently anomalous behavior below 1.6 MeV and the changes in slope in the multiple-chance-fission-energy regions will be resolved.

The available data are plotted in Fig. IX-1. There is a steady increase of $\bar{\nu}_p$ with neutron energy over most of the energy range. However, near threshold, there is a narrow region where $\bar{\nu}_p$ appears to decrease with increasing energy. The experimental errors are comparable with the observed decrease but the effect has been observed in three separate $\bar{\nu}_p$ measurements (IX-9, -10, and -11) so it is probably real. Furthermore, a change in the kinetic energy of the fission fragments has been observed in this region (IX-15).

When only the presently available experimental data are considered, an adequate description of the energy dependence of $\bar{\nu}_p$ for ^{232}Th is given by

$$\bar{\nu}_p = (3.482 \pm 0.033) - (0.891 \pm 0.034)E_n \qquad E_n < 1.57 \text{ MeV},$$

$$\bar{\nu}_p = (1.8098 \pm 0.0051) + (0.1632 \pm 0.0007)E_n \qquad E_n > 1.57 \text{ MeV}.$$

The above equations were obtained by weighted least squares fits to all the data in Table IX-1. Weights were based on the errors assigned by the authors. The results are shown by the dashed curves in Fig. IX-1.

The experimental data are insufficient to show the small changes in slope observed for some other fissionable isotopes (e.g., IX-1) and usually associated with second or third chance fission. However, a method for predicting $\bar{\nu}_p$ has been developed by Howerton (IX-17). It accounts for multiple chance fission and depends only on the charge, mass and binding energy of the last neutron. It agrees very well with experimental data when applied to other isotopes. The result of applying this method to ^{232}Th from 1.6 to 20 MeV is shown in Fig. IX-1 by the solid curve. It agrees very well with the experimental data except near 14 MeV and, even there, differs by less than 5 percent from the more recent data.

The recommended values are given in Table IX-2 and are illustrated in Fig. IX-1 by the solid curve. The values above 1.6 MeV were calculated according to Ref. IX-17. The agreement with the experimental data at the lower energies is adequate. This, combined with the wide scatter in the data near 14 MeV, and the lack of measurements over much of the energy range, makes these calculated values the best available. The energy dependence below 1.6 MeV is uncertain. The recommended curve should be correct in a qualitative sense. It is very probable that there is a step in the curve due to the opening of a new fission channel but its magnitude is uncertain.

C. Energy Spectrum

Data on the prompt-neutron energy spectrum for ^{232}Th fission are scant. There appears to be only a single measurement (IX-8) which was made at 14.3 MeV. The neutron spectrum in the energy range 0.3-5 MeV was measured by time-of-flight in coincidence with fission events. The results were described by a distribution of the form

$$F(E) = \alpha F_1(E) + (1 - \alpha)F_2(E),$$

$$F_1(E) = (E/T^2)\exp(-E/T),$$

$$F_2(E) = \exp(-E_f/T_f)\exp(-E/T_f)\sinh(2\sqrt{EE_p}/T_f) \times (\pi E_f T_f)^{-1/2}.$$

where E_f is the energy of a neutron having the velocity of a fission fragment. The parameters T, T_f and α were determined by least-squares fitting.

$$T_f = 1.17 \pm 0.03 \text{ MeV},$$

$$T = 0.38 \pm 0.04 \text{ MeV},$$

$$\alpha = 0.25 \pm 0.02.$$

An earlier measurement (IX-16), also at 14 MeV, is not really a fission spectrum determination since it did not have the fission coincidence requirement. It gave:

$$T_f = 1.2 \text{ MeV},$$

$$T = 0.54 \pm 0.05 \text{ MeV},$$

$$\alpha = 0.80 \pm 0.05.$$

The values of T_f are very similar.

In a similar but more extensive experiment, Batchelor et al. (IX-18) measured the secondary-neutron emission spectrum for incident neutron energies of 3, 4, and 7 MeV. By assuming Maxwellian temperatures for the fission neutrons of 1.26, 1.30, and 1.26 MeV respectively (obtained from a modification of Terrell's formula of 1959 (IX-19)) they were able to obtain calculated spectra that were consistent with their data when they used reasonable evaporation temperatures for the (n;n') secondary neutrons.

In view of the lack of experimental data,the energy spectra of the prompt neutrons associated with ^{232}Th fission are calculated. They are composites, taking into account fission neutrons from the (n;f), (n;n'f), etc. reactions and the pre-fission evaporation neutrons. The form used for the fission neutrons is

$$P_m(E) = F_m(2/(\sqrt{\pi}T_m^{3\ 2}))\sqrt{E}\ \exp(-E/T_m),$$

where F_m is the fraction of the total neutrons which come from fission mode m, and T_m in the Maxwellian temperature.

The form used for the evaporation neutrons is

$$P_n(E) = \{(F_n/T_n^2)/(1 - (1 + E_{max}/T_n^2)\ \exp(-E_{max}/T_n)\}$$
$$\cdot\ E\ (\exp((-E/T_n)),$$

where F_n is the fraction of the total number of neutrons resulting from the pre-fission neutrons in mode n, T_n is the temperature of the evaporation neutron, and E_{max} is the maximum energy these neutrons can have and still leave the residual nucleus with sufficient energy to fission.

The Maxwellian temperature, T_m, of the fission neutrons is based on a relation between T_m and $\bar{\nu}_p(E)$. Howerton and Doyas (IX-20) reviewed the available data and obtained an equation to represent the Maxwellian temperatures of the fission spectra

$$T_n = 0.997 + 0.125\ \bar{\nu}_p(E),$$

where

$$\bar{\nu}_p = \frac{\bar{\nu}_p(E)\sigma_f(E) - \sigma_{n,n'f}(E) - 2\sigma_{n,2n'f}(E) - \ldots.}{\sigma_f(E)},$$

and $\bar{\nu}_p(E)$ is the total number of fission neutrons plus any (n;n') neutrons. The values of $\sigma_{n,f}$ and $\sigma_{n,n'f}$ etc. can be estimated by assuming that direct fission and successive-chance fission remain essentially constant fractions of the nonelastic cross section above each of the successive-chance fission thresholds.

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TABLE IX-1. Renormalized Measurements of $\overline{\nu}_p$ for ^{232}Th

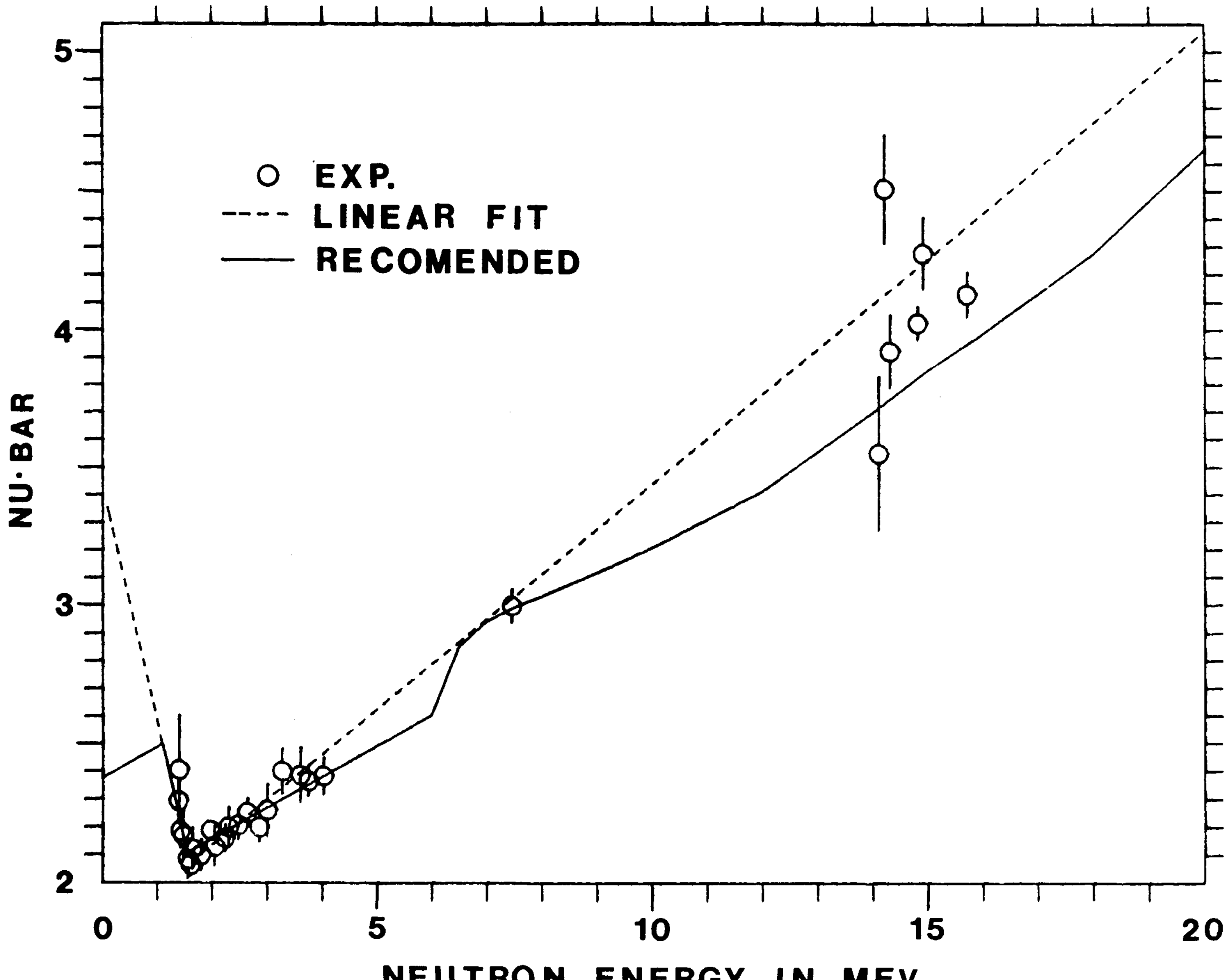
	Reference	Standard	E_n (MeV)	ν_p
IX-3.	Johnston (1956)	Ra-Be Source	14.1	3.55 ± 0.28
IX-4.	Smith et al. (1959)	^{238}U (1.4 MeV)	1.4	2.404 ± 0.196
IX-5.	Leroy (1960)	^{235}U (th.)	14.2	4.508 ± 0.194
IX-6.	Conde and Starfelt (1961)	^{252}Cf (spon.)	3.6[a]	2.388 ± 0.027
			14.9[a]	4.365 ± 0.035
IX-7.	Kuzminov (1963)	^{235}U (th.)	2.30	2.196 ± 0.072
			3.75	2.364 ± 0.056
			15.70	4.128 ± 0.080
IX-8.	Vasil'ev et al.	^{235}U (14.3 MeV)	14.3	3.921 ± 0.132
IX-9.	Mather et al. (1965)	^{252}Cf (spon.)	1.39	2.291 ± 0.074
			1.98	2.185 ± 0.028
			3.00	2.259 ± 0.093
			4.02	2.382 ± 0.065
IX-10.	Conde, Holmberg (1965)	^{252}Cf (spon.)	1.42	2.183 ± 0.060
			1.61	2.063 ± 0.038
			1.80	2.098 ± 0.055
			2.23	2.158 ± 0.049
			2.64	2.250 ± 0.052
			3.60[a]	2.386 ± 0.099
			7.45	2.998 ± 0.060
			14.8	4.024 ± 0.060
			14.9[a]	4.276 ± 0.129
IX-11.	Prokhorova, Smirenkin (1968)	^{235}U (0.37 MeV)	1.48	2.166 ± 0.094
			1.56	2.083 ± 0.072
			1.64	2.120 ± 0.074
			2.05	2.129 ± 0.072
			2.48	2.206 ± 0.057
			2.86	2.198 ± 0.057
			3.27	2.400 ± 0.081

[a]The 3.6 and 14.9 MeV values reported in Ref. IX-10 are renormalized values.

TABLE IX-2. Recommended Values for $\bar{\nu}_p$ for ^{232}Th Neutron Induced Fission

E_n	$\bar{\nu}_p$	E_n	$\bar{\nu}_p$
0	2.376	9.000	3.121
1.102	2.500	10.00	3.211
1.545	2.106	12.00	3.416
6.000	2.605	14.00	3.701
6.500	2.855	15.00	3.855
7.000	2.943	16.00	3.989
7.500	2.994	18.00	4.276
8.000	3.035	20.00	4.652

IX-1. Comparison of Evaluated and Measured $\overline{\nu}_p$ Values for ^{232}Th as Discussed in the Text. (ANL-116-77-725).



X. PHOTON PRODUCTION PROCESSES

Photon production from neutron-induced reactions is dealt with separately for two energy regimes. For neutron energies less than the threshold for inelastic scattering, the only process that contributes to photon production is neutron capture. Thus for $E_n \leq 50$ keV photon production is represented by an energy dependent multiplicity to be applied to the (n,γ) cross section and by an energy-independent spectrum. The spectrum used was based on an undocumented measured spectrum for ^{238}U with a minor adjustment for the small Q-value difference between ^{232}Th and ^{238}U. The average energy of the assumed spectrum was then divided into the Q-value to obtain a multiplicity at zero neutron energy. The multiplicity at 50 keV was obtained (X-1) by use of the formula $M(E) = M_0(E_n + Q)/Q$ where M_0 is the multiplicity at zero neutron energy as described above.

For incident neutron energies greater than 0.05 MeV the method of Perkins, Haight and Howerton (X-2) was used to calculate photon production cross sections and spectra. For the spectrum of photons from fission the data of Peele and Maienschein (X-3) for ^{235}U thermal neutron fission were used in the calculation. As stated in Section IV of this report the branching ratios for deexcitation of levels both within and between bands of levels is highly uncertain. For this reason, explicit production of photon lines associated with inelastic scattering was not chosen for the photon production files. The calculated values have the characteristic of preserving energy conservation. Energy conservation could be forced with photon line excitation cross sections, but both economy of presentation and adherence to the principal that one should not seek over complexity provided the reason for using the formalism of Ref. X-2.

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XI. DATA TESTING

The only meaningful integral experiment against which this evaluation can be tested is a relatively recent nominally 14 MeV pulsed sphere experiment (XI-1) done at the Lawrence Livermore Laboratory as one of a series of such experiments (XI-2).

A source of nominally 14 MeV D-T neutrons is produced at the center of a spherical shell of ^{232}Th with a thickness of one mean free path for 14 MeV neutrons. The time spectra of emergent neutrons are measured at 26° and 120° with respect to the direction of the incident deuteron beam at a distance of about 9.5 meters from the sphere.

The experiment can be described exactly and the time spectra calculated with the TARTNP (XI-3) Monte Carlo neutronics code. Figures XI-1 and -2 display the calculated and experimental spectra for 26° and 120° angles, respectively. A relatively good measure of the validity of the non-elastic cross section in the 14-15 MeV region can be obtained from the integral under the peak that lies between 175 and 200 nanoseconds. The peak is an approximate measure of the transmitted and elastically scattered neutrons. The integral from the peak to the longest flight time is a measure of the non-elastic cross section and spectra from the nominally 14 MeV source neutron energy to 2 MeV. Table XI-1 represents the experimental and calculated integrals. The agreement between experiment and calculation is excellent for both the spectra and the integrals especially since the experiment was used only for checking the evaluation and no data adjustment was done to force a fit, although the energy distributions for the (n,n') pre-equilibrium neutrons were derived from information obtained from the total pulsed sphere program.

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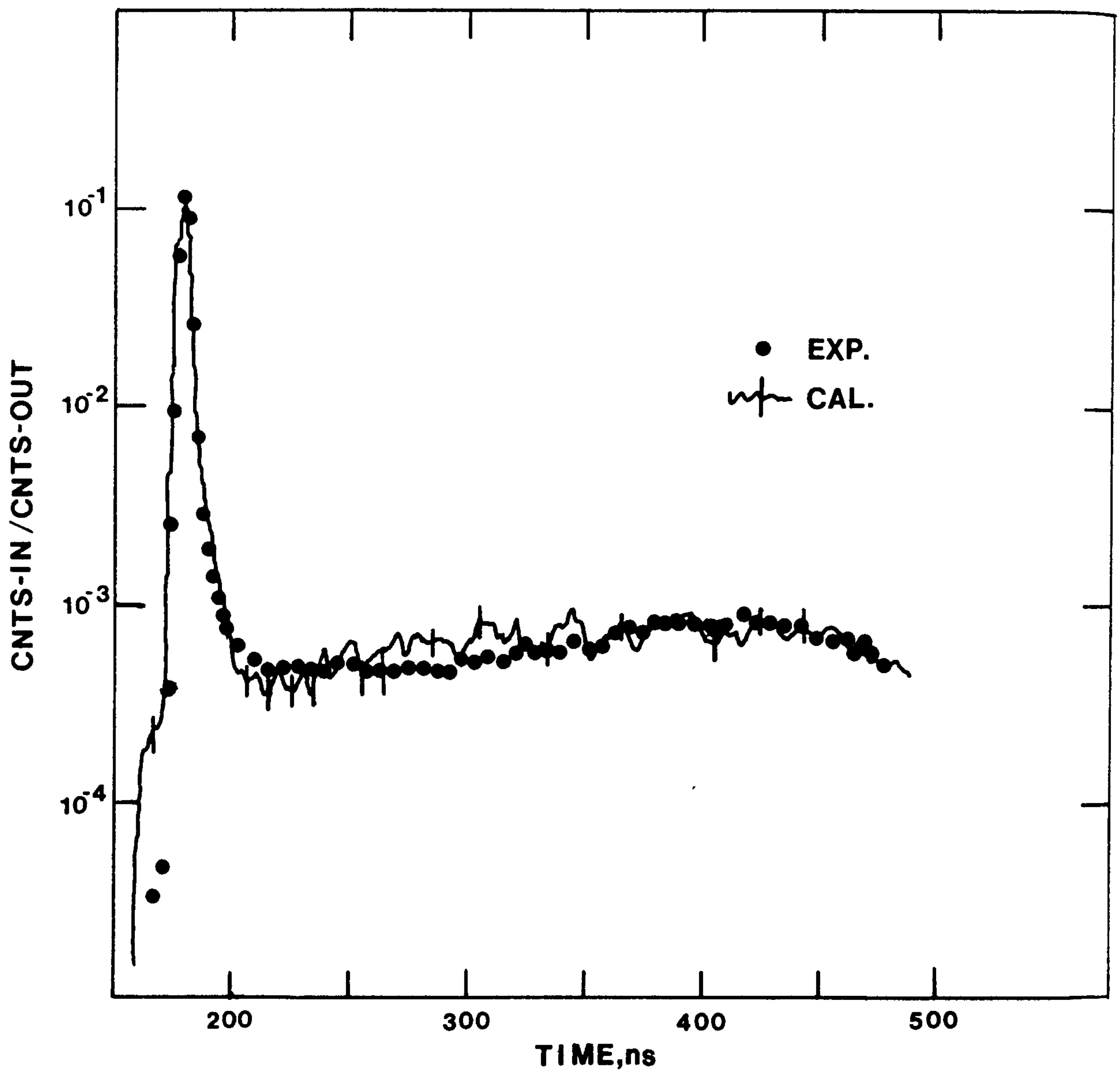
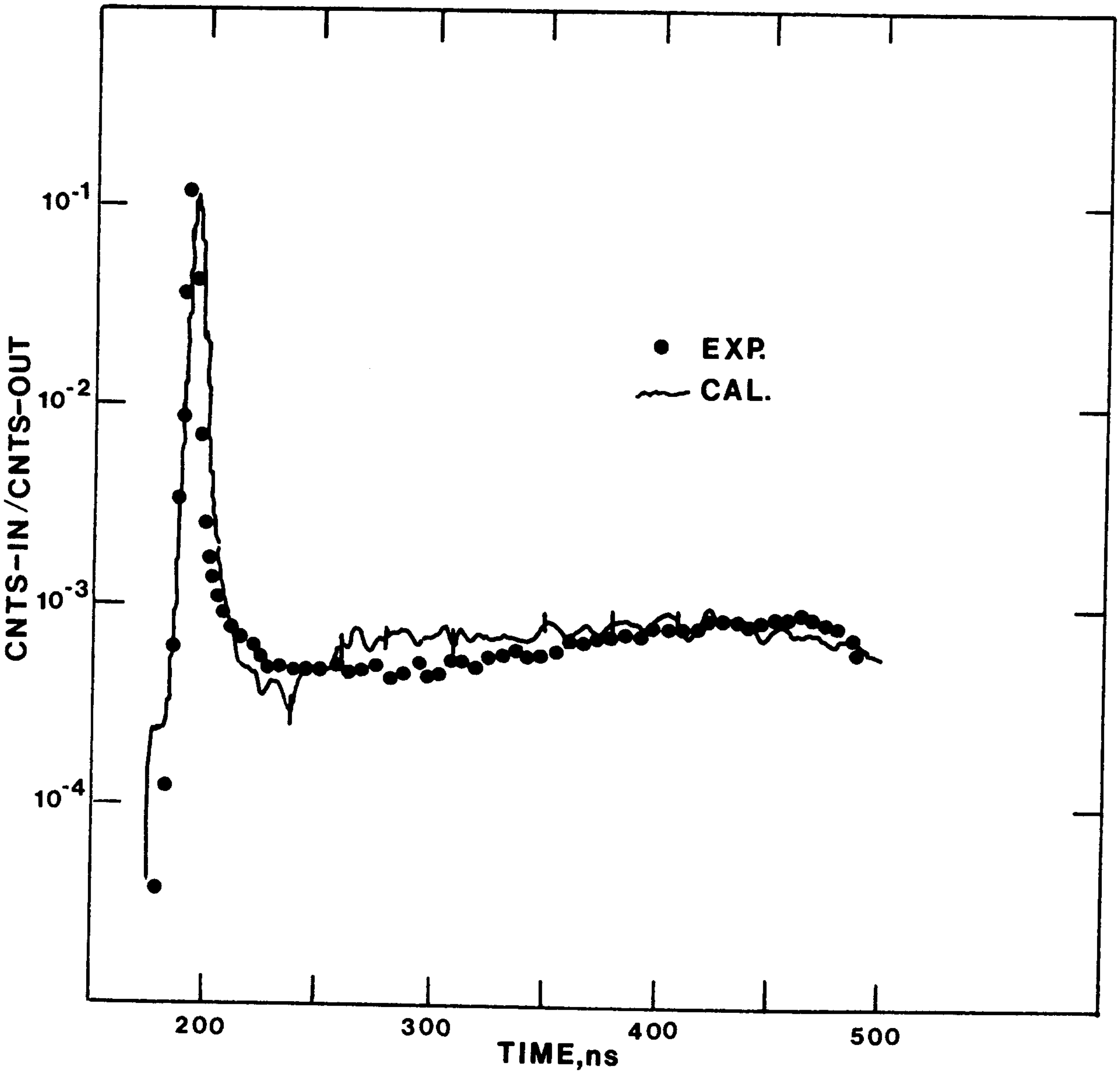
XI-3. E. F. Plechaty and J. R. Kimlinger "TARTNP, A Coupled Neutron-Photon Monte Carlo Transport Code," Lawrence Livermore Laboratory Report UCRL-50400, Vol. 14 (1976).

TABLE XI-1. Comparisons of Experimental and Calculated Integrals

	Elastic Peak			11.8 MeV to 2 MeV			Incident Energy to 2 MeV		
Angle	Calc	Exp	C/E	Calc	Exp	C/E	Calc	Exp	C/E
26°	.636	.636	1.000	.181	.178	1.017	.817	.814	1.004
120°	.683	.680	1.004	.194	.178	1.090	.877	.858	1.022



XI-1. Comparison of Measured and Calculated Emergent Neutron Spectra for a Nominally 14 MeV Pulsed Sphere with a Thickness of 1.0 mfp (see Ref. XI-2) at an Observation Angle of 26° as Described in the Text.



XI-2. Comparison of Measured and Calculated Emergent Neutron Spectra for a Nominal 14 MeV Pulsed Sphere with a Thickness of 1.0 mfp (see Ref. XI-2) at an Observation Angle of 120° as Described in the Text.

XII. CONCLUDING REMARKS

This work reasonably meets the first objective of providing a contemporary evaluated nuclear data file for ^{232}Th. With the extension provided to lower energies, this file is suitable for the assay of the neutronic performance of ^{232}Th-associated nuclear energy systems. In some areas this evaluation is based upon fragmentary physical information and, as a consequence, the file must be considered an interim evaluation pending the availability of more definitive experimental and theoretical microscopic data.

In the course of the evaluation, a detailed review of the available microscopic data was carried out. From this review it is possible to set forth guidelines for future measurements necessary for an appreciable improvement of the evaluation. These measurement guidelines are as follows.

Precise total cross sections are a key to a successful evaluation and are directly utilized in neutronic calculations. In the present ^{232}Th context the primary region of concern is below 5 MeV.

- Measurements should provide the neutron total cross sections of ^{232}Th to 1-2 percent accuracies to 5 MeV. Energy resolutions need to be no better than 5-10 percent. Such measurements are a high priority. Uncertainties are large above $\gtrsim$14 MeV but less critical to most applications. Thus, high-energy measurements should be pursued, but with a lower priority.

The above measurements are relatively simple and the results will impact on a number of critical areas (e.g., inelastic scattering) via the nonelastic cross section. The reasonable accuracy objective of the measurements is an order of magnitude smaller than the difference between the present evaluation and that of ENDF/B-IV.

Reliable and recent measurements of the elastic scattering cross sections of ^{232}Th are limited to energies of 1.5 and 2.5 MeV. Lower-energy values are the result of very old measurements and are far less precise.

- The neutron differential elastic scattering cross section of ^{232}Th should be determined to $\lesssim$10 percent accuracies at ~250 keV intervals from ~0.25 to 3.0 MeV. The measurements should be given high priority.

These measurements are not easy but they are technically feasible and, together with the total cross section, will determine the key nonelastic cross section in the critical areas. Above 3.0 MeV it will be very difficult to determine elastic scattering cross sections free of inelastic scattering perturbation. Thus the currently available information will probably suffice for the time being. An exception is the important ~14 MeV energy where verification measurements would be useful.

The ^{232}Th neutron inelastic scattering situation is similar to that of the elastic scattering process, above. The cross sections are large and important in many applications.

- Inelastic neutron scattering cross sections of ^{232}Th should be measured to ~10 percent accuracies at intervals of ~250 keV from ~0.25 to 3.0 MeV. The scattered neutron resolution should be such as to clearly resolve the excitation of the first few states and to provide cross sections with scattered-neutron resolutions of ~100 keV for excitation of ~1.0 to 2.0 MeV. These measurements should be pursued with a high priority.

In addition, pseudo-integral measurements at ~14 MeV, similar to those pursued in the Lawrence Livermore Laboratory pulsed-sphere program, would be very useful in determining the characteristics of high-energy inelastic scattering processes.

Fission cross sections of ^{232}Th are not as important in ^{232}Th/^{233}U systems as ththose of ^{238}U in ^{238}U/^{239}Pu systems due to their generally small size. However, the data base is poor particularly at higher energies (e.g., 14 MeV).

- ^{232}Th absolute fission cross sections and their ratios to ^{235}U and ^{238}U should be measured to $\leq$5 percent accuracies to 20 MeV with medium priority.

Such results would help to refine the evaluated data file.

The neutron radiative capture cross sections are large and a more sensitive matter in Th/^{233}U systems than those of ^{238}U in the ^{238}U/^{239}Pu systems. The data base is poorly defined with large relative and absolute discrepancies, particularly the latter.

- High priority should be given to the measurement of ^{232}Th absolute and relative capture cross sections from 0.025 to 2.0 MeV. Suggested reference cross sections for the relative measurements are ^{238}U capture and ^{235}U fission. Modest energy resolutions of $\sim$10 percent are suitable. Accuracy objectives should be 5 percent (i.e., 2-5 times improvement over present status).

The (n;2n') cross sections of ^{232}Th are reasonably known. However, more precise measurements would refine the evaluated file.

- The (n;2n) cross sections of ^{232}Th should be determined to $\sim$5-10 percent accuracy from threshold to 20 MeV with major emphasis below 14 MeV. Five percent energy resolutions are suitable. The effort should be given moderate priority.

The (n;3n') cross sections remain very uncertain and the values are large.

- The (n;3n') cross sections should be measured with a first accuracy objective of 10-20 percent. The energy range is threshold to 20 MeV with 10 percent-energy resolution. Reasonably high priority should be assigned to these measurements due to the impact on other reaction channels.

The (n;2n') measurements would involve both prompt detection and activation techniques. Only the former appears suitable for (n;3n') determinations.

As noted above, fission in ^{232}Th is not as critical in Th/^{233}U systems as that of ^{238}U in U/Pu systems. Thus prompt and delayed fission-neutron properties are not as sensitive matters. However, uncertainties in both areas are very large indicating that associated measurements should be pursued with moderate priority. Such measurements are:

- Determination of total delayed-neutron yields of ^{232}Th to 5 percent accuracy both above and below the (n;n',f) threshold.
- Determination of the differential energy spectrum of ^{232}Th delayed neutrons to $\sim$20 percent accuracy.

- Measurement of ^{232}Th precursor periods and yields to 10 percent accuracy both below and above the (n;n',f) threshold.

- Absolute measurement of ^{232}Th nu-bar ~0.5 MeV above threshold and, subsequently, energy dependence relative thereto. Accuracies should be 5 percent or better and incident neutron energy resolutions 5-10 percent.

Current evidence suggests that these, and other, aspects of the ^{232}Th fission process will show large fluctuations with incident neutron energy.

When definitive results from the experimental program suggested above become available, a re-evaluation of the fast-neutron portions of the present file will be warranted.

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