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ANL/NDM-105

Neutronic Evaluated Nuclear-Data File for Vanadium

by

A.B. Smith, D.L. Smith, P.T. Guenther, J.W. Meadows,
R.D. Lawson, R.J. Howerton, T. Djemil, and B.J. Micklich

May 1988

ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.

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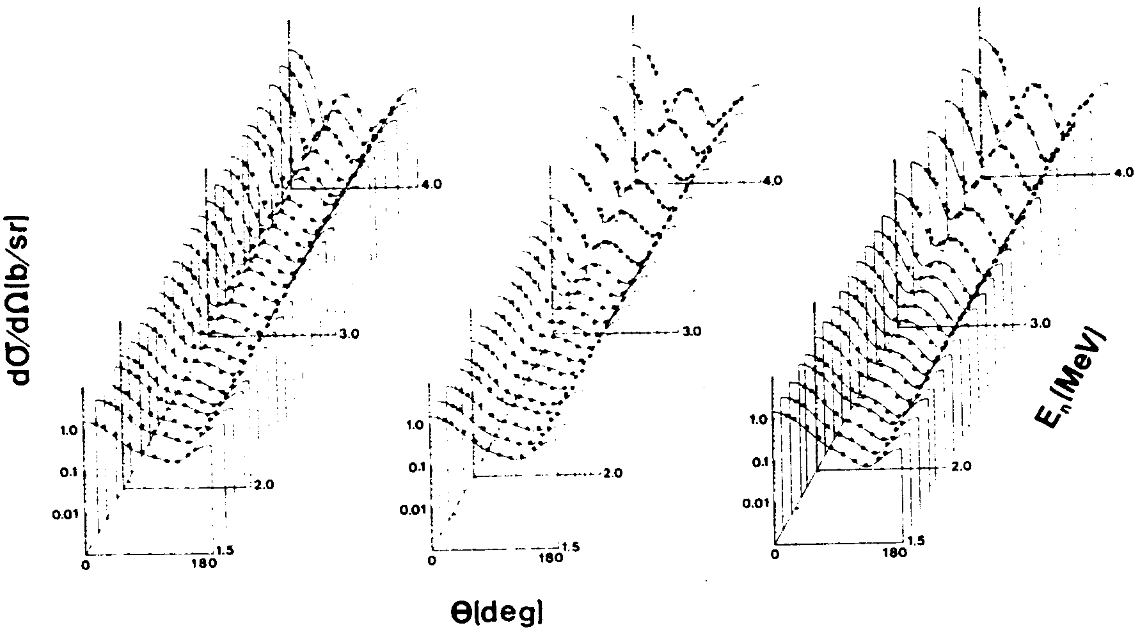

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ABSTRACT

A comprehensive neutronic evaluated nuclear-data file for vanadium is described. The file extends from 10^{-5} eV to 20.0 MeV and contains all neutron-induced processes of significance in applied neutronic calculations associated with both fusion- and fission-energy development, including: i) the neutron total cross section, ii) elastic and inelastic scattering cross sections and associated neutron-emission spectra, iii) neutron radiative-capture cross sections, iv) the (n,2n) process, v) neutron-induced charged-particle-emission processes, and vi) neutron-induced photon production. Attention is given to uncertainty specification for the prominent processes. The corresponding numerical file is developed in ENDF/B-VI formats and has been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory.

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I. INTRODUCTION

This document outlines the physical considerations and evaluation procedures involved in the provision of an evaluated nuclear-data file of vanadium. The objective of the work is a comprehensive evaluated file for neutronic applications, particularly those associated with the development of fusion- and fission-energy systems. Certain aspects of the file may find special uses (e.g., dosimetry studies), but those individuals having unusual needs not covered by this neutronic file should address special-purpose files tailored to their interests. Elemental vanadium consists of two isotopes, ^{50}V and ^{51}V. This file is nominally an elemental file, but gives no consideration to the very minor isotope ^{50}V (0.25% abundant). This approximation should be of no concern in the vast majority of neutronic applications. The evaluation gives attention to new physical understanding, particularly the detailed experimental and theoretical studies reported in the complementary document.[1] This new insight, into both models and observables, results in considerable improvement over the previously available evaluated data, and to new or better definition in many areas. An additional factor contributing to improvement is the use of rigorous statistical methods[2] in the evaluation of experimental information. The latter approach mitigates subjective bias, and provides an improved definition of evaluation uncertainties and their correlations. The uncertainties are cited throughout the narrative of this document. In a number of cases they follow from quantitative numerical analysis, and in those instances they are quantitatively specified in the numerical portions of the file. In a number of other instances the uncertainty estimates must follow essentially from subjective judgements. These latter subjective estimates were not included in the numerical file to avoid the implication that they were derived in a quantitative manner. Users who are interested in these qualitative and subjective uncertainties will find them cited throughout the text.

The associated numerical file is expressed in ENDF/B-VI format. The primary version of the file assumes isotropic continuum-neutron emission, as that formulation is most widely consistent with commonly used processing codes. A secondary version includes angle-dependent energy distributions of emitted continuum neutrons. The file has not been reviewed in the context of clean integral benchmarks (e.g., pulsed spheres), since no suitable benchmarks have apparently been measured. The numerical file has been checked using ENDF checking codes and subsequently transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. Interested parties should obtain a copy of the numerical file from the latter institution, or they may contact the authors.

Subsequent portions of this document address specific sections of the file.

II. NEUTRON TOTAL CROSS SECTIONS

An essential basis of an evaluated neutronic file is the precise determination of the neutron total cross section. The total cross section is the envelope to which the partial cross sections must exactly conform, and some of the components of the file are determined by constructing the difference between partial and total cross sections. Throughout the file, rigorous cross-section consistency as a function of energy is mandatory; thus, errors in the total cross section will be reflected elsewhere in the file. Certain physical checks are no more valid than the total cross section. Of all the cross sections, only the total cross section can be measured in a simple, self-normalizing manner that makes possible, in principle, its precise determination. Nevertheless, there are experimental perturbations which are probably the sources of persistent experimental discrepancies. In view of the key importance of the total cross section, considerable attention is given to it in the present evaluation.

A. Resonance Parameters

The resonance-parameter representation is employed for incident energies from 2.0 to 100 keV using, s- and p-wave parameters of V-51. The resonance parameters were taken directly from the compilation of Mughabghab et al.,[3] as supplemented by Mughabghab and Dunford.[4] Negative-energy resonances of that compilation were abandoned and a small background introduced to assure low-energy cross-section values consistent with thermal values of Ref. 3 and other experimental data. The neutron scattering and capture cross sections were reconstructed from the parameters and background cross sections using the code RECENT,[5] and the results are shown in Fig. 1. These resonance parameters are based upon relatively old data which shows a considerable variation in quality and some pronounced discrepancies with respect to both energy scale and resolution. There is a need for resonance studies, using contemporary high-resolution techniques, to at least 200 keV. Until such new experimental information becomes available, it will be difficult to improve on the present resonance parameterization. The present resonance evaluation cannot be directly compared with that of ENDF/B-V,[6] as the latter uses a point-wise representation of the resonance region. The two evaluations should be very similar, as the data base has not appreciably changed during the intervening period, but the resonance parameters of the present evaluation are more suited for use in some processing codes.

B. Energy-averaged Neutron Total Cross Sections

A comprehensive experimental neutron-total-cross section data base was constructed from the literature, as referenced in CINDA[7] and as available from the compiled files of the National Nuclear Data Center. This data base was augmented with values obtained from independent literature searches and from measurements undertaken by the authors.[8]

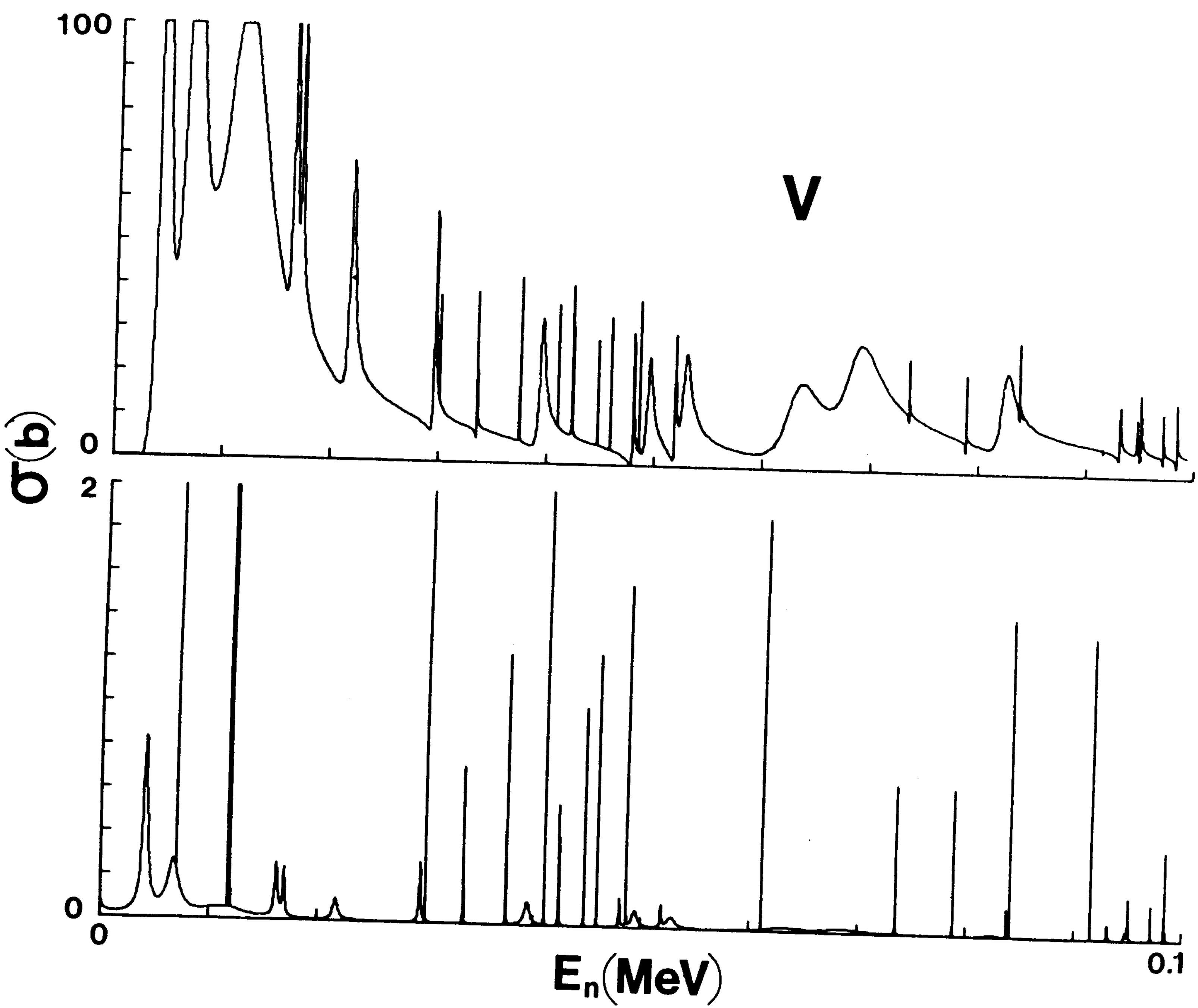

Fig. 1. Scattering (upper) and capture (lower) cross sections derived from the evaluated resonance parameters. Neither figure is inclusive of the small continuum background noted in the text.

The data base extended from the upper bound of the resonance region (100 keV) to 20.0 MeV. The citations of the individual data sets are given in Refs. 1 and 8-31. As noted therein, not all of these data sets were applicable to the energy range of interest. The majority of the lower-energy data strongly fluctuate with energy due to partially resolved and prominent resonances. Thus, these data sets were averaged over intervals of 200 keV at the lower-energy extreme, approximately linearly increasing to a 500 keV averaging increment at 20.0 MeV. The fluctuations persisted to some extent at the lower energies even in these averaged values. The individual averaged data sets were inspected using large-scale plots, and obviously erroneous data sets and/or data values were deleted from the data base. Generally, the reported neutron total cross sections were derived from conventional transmission measurements[32] and were thus actually "effective" cross sections, meaningful only within the context of the resolutions employed in the respective measurements. In particular, at lower energies the experimental results may be distorted by self-shielding effects that are very difficult, if not impossible, to assess from the available published information. The consequence is that, on the energy average, the reported fluctuating cross sections at lower energies may be systematically distorted toward too-low values by several percent. The distortions will be largest for those experiments using the thickest samples and lesser resolutions. Only one set of measurements[1] experimentally examined such effects, and they were found to be relatively small above 1.0 MeV. That will not necessarily be so at lower energies. An effort to make self-shielding corrections, using unresolved-resonance representations was not attempted, as too often the necessary quantitative specification of the experimental conditions was not available (e.g., sample thickness). In very nearly all of the data sets only statistical uncertainties were given. These were generally small and clearly were not sufficient to account for the discrepancies between data sets. In the absence of quantitative information, systematic uncertainties were estimated using subjective judgement. A consideration was the concurrent measurement of a reference standard such as carbon. Unfortunately, there were few such verification measurements. Throughout, the statistical and the systematic uncertainties were propagated through the above averaging procedures. The resulting energy-averaged data base is shown in Fig. 2.

The evaluation was constructed from the above energy-averaged data base using the statistical processing code GMA.[2] That code rigorously constructs the "best" evaluated data set to a predetermined mesh from the experimental data base, and provides the associated evaluation covariance matrix. The latter is, of course, a reflection of the subjective judgments of systematic uncertainties cited above, and should therefore be used as qualitative guidance rather than quantitative definition. The numerical uncertainty values are given in Table 1, and are specified in the file. They should be interpreted as referring to the energy-averaged cross-section behavior and not to the detailed resonance structure cited above.

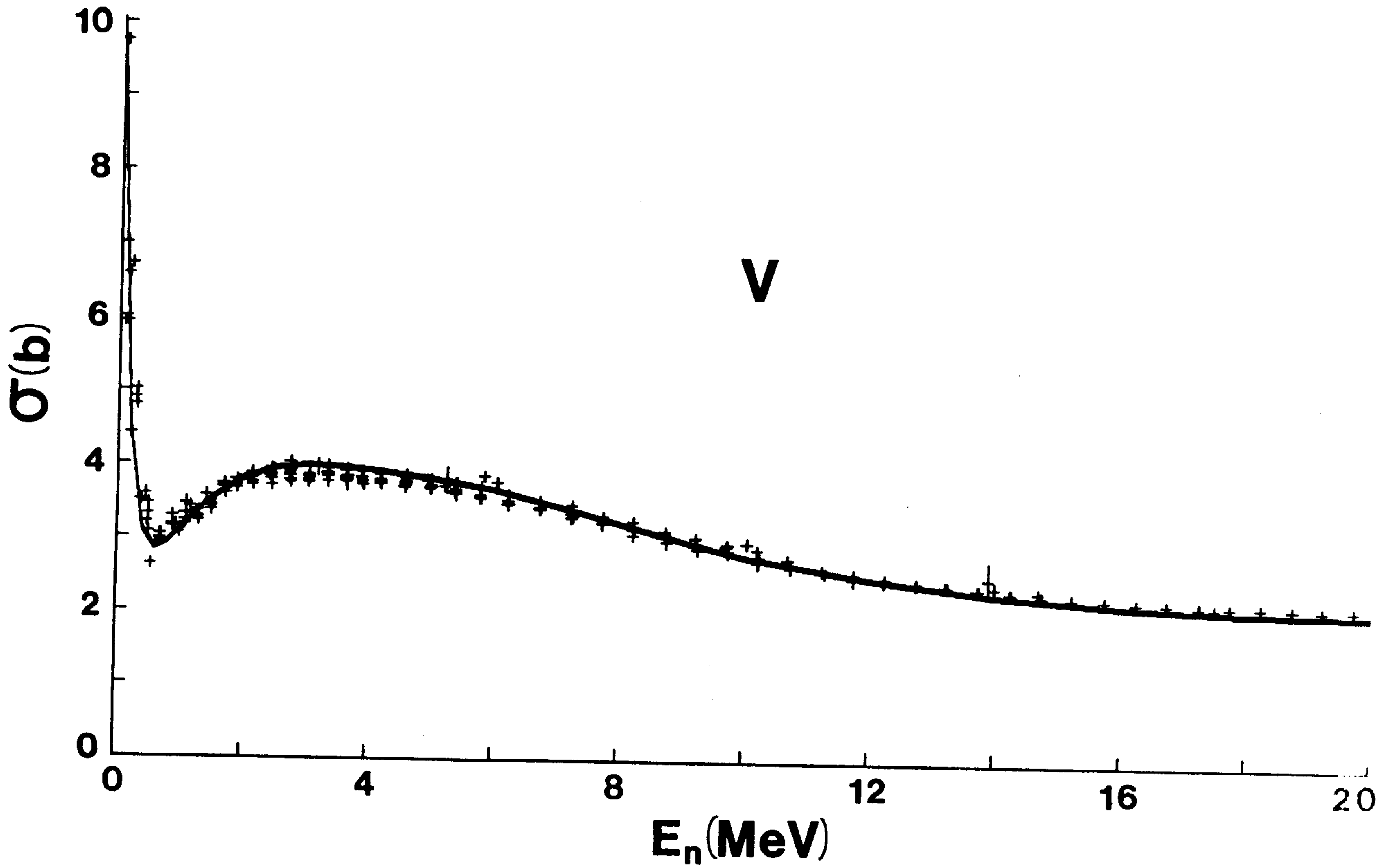

Fig. 2. Energy-averaged data base (symbols) and resulting energy-averaged evaluation (curve).

Table 1-A. Energy-Averaged Total-Cross-Section Uncertainties

Energy (MeV)	Uncertainty in %
< 0.1	4.0
0.1	3.6
0.2	3.0
0.5	2.6
1.0	2.2
2.0	2.2
4.0	2.0
6.0	2.4
8.0	3.0
10.0	3.0
12.0	3.2
14.0	3.0
16.0	3.2
18.0	3.4
20.0	4.2

Table 1-B. Error Correlation Matrix

1.00														
0.18	1.00													
0.17	0.24	1.00												
0.21	0.21	0.25	1.00											
0.24	0.24	0.27	0.51	1.00										
0.25	0.24	0.26	0.49	0.69	1.00									
0.25	0.25	0.26	0.47	0.65	0.64	1.00								
0.20	0.20	0.19	0.26	0.31	0.32	0.35	1.00							
0.22	0.21	0.21	0.28	0.33	0.34	0.38	0.32	1.00						
0.22	0.21	0.21	0.28	0.33	0.35	0.38	0.32	0.34	1.00					
0.22	0.21	0.21	0.28	0.33	0.34	0.37	0.31	0.34	0.34	1.00				
0.22	0.21	0.21	0.28	0.33	0.34	0.38	0.32	0.34	0.34	0.34	1.00			
0.22	0.21	0.21	0.28	0.33	0.35	0.37	0.30	0.32	0.32	0.31	0.32	1.00		
0.21	0.21	0.20	0.27	0.32	0.33	0.35	0.29	0.30	0.31	0.30	0.30	0.32	1.00	
0.21	0.21	0.21	0.27	0.31	0.32	0.34	0.27	0.29	0.29	0.29	0.29	0.30	0.29	1.00

The above experimentally-derived evaluated data set displayed small fluctuations due to variations in the underlying experimental data. These were smoothed by chi-square fitting the experimentally-derived evaluated data with a conventional spherical optical model. Ten parameters were varied in the fitting procedure: real and imaginary radii and diffuseness, and real and imaginary strengths (each given a quadratic energy dependence). The resulting optical-model parameters are physically rational but should not be construed as more than a parameterization of the evaluated data for the purposes of smoothing. The model-calculated results agreed with the experimentally-based evaluated cross sections to within the uncertainties of Table 1, excepting at the very lowest energies (e.g., below 0.3 MeV), where the evaluation is particularly sensitive to large resonance fluctuations and the above-cited self-shielding effects are a concern. Thus, the model-smoothed results were taken for the energy-averaged evaluation.

Below approximately 5.0 MeV the resonance fluctuations of the higher-resolution data become increasingly larger as the energy decreases. These fluctuations were introduced into the evaluation by subjectively selecting the highest-resolution experimental results over given energy ranges and normalizing them so that their average was consistent with the energy-averaged evaluation. For this purpose, Ref. 22 was used up to 220 keV, Ref. 8 from 220-360 keV, and Ref. 15 from 0.36 - 6.0 MeV. Ref. 8 is very old and does not have the high resolution of contemporary measurements, but it is the best information available in this energy range. The lack of high-resolution total-cross-section information in the energy range 200-500 keV is, unfortunately, endemic throughout the periodic table. The final result is an evaluation that has the energy-averaged magnitudes determined above, and yet retains the details of the fluctuating structure. Of course, the structure will follow the magnitude and/or energy scale variations inherent to the measurements upon which it was based, and thus in specific detail may not be the "true" value. On the average, such variations will be of no concern in neutronic applications, but the user should be aware that the characterization of a specific resonance may not exactly correspond to physical reality or to the results of subsequent measurements. This shortcoming cannot be avoided, given the status of the available data base. The final evaluated cross sections, above the discrete resonance region, are illustrated and compared with those of ENDF/B-V in Fig. 3. The two evaluations are reasonably consistent in this figure. (However, close inspection of the results on a linear scale, as in Fig. 5, shows that the values of the present evaluation are smaller than those of ENDF/B-V from ≈ 7.0-16.0 MeV by up to ≈ 10%.) These changes are due to improved experimental information and models, particularly the work of Ref. 1. It is interesting to note that there is a periodicity to the lower-energy resonance structure that is not evident in neighboring nuclei (e.g., in Co-59), a tendency that is consistent with the concept of doorway processes.[1]

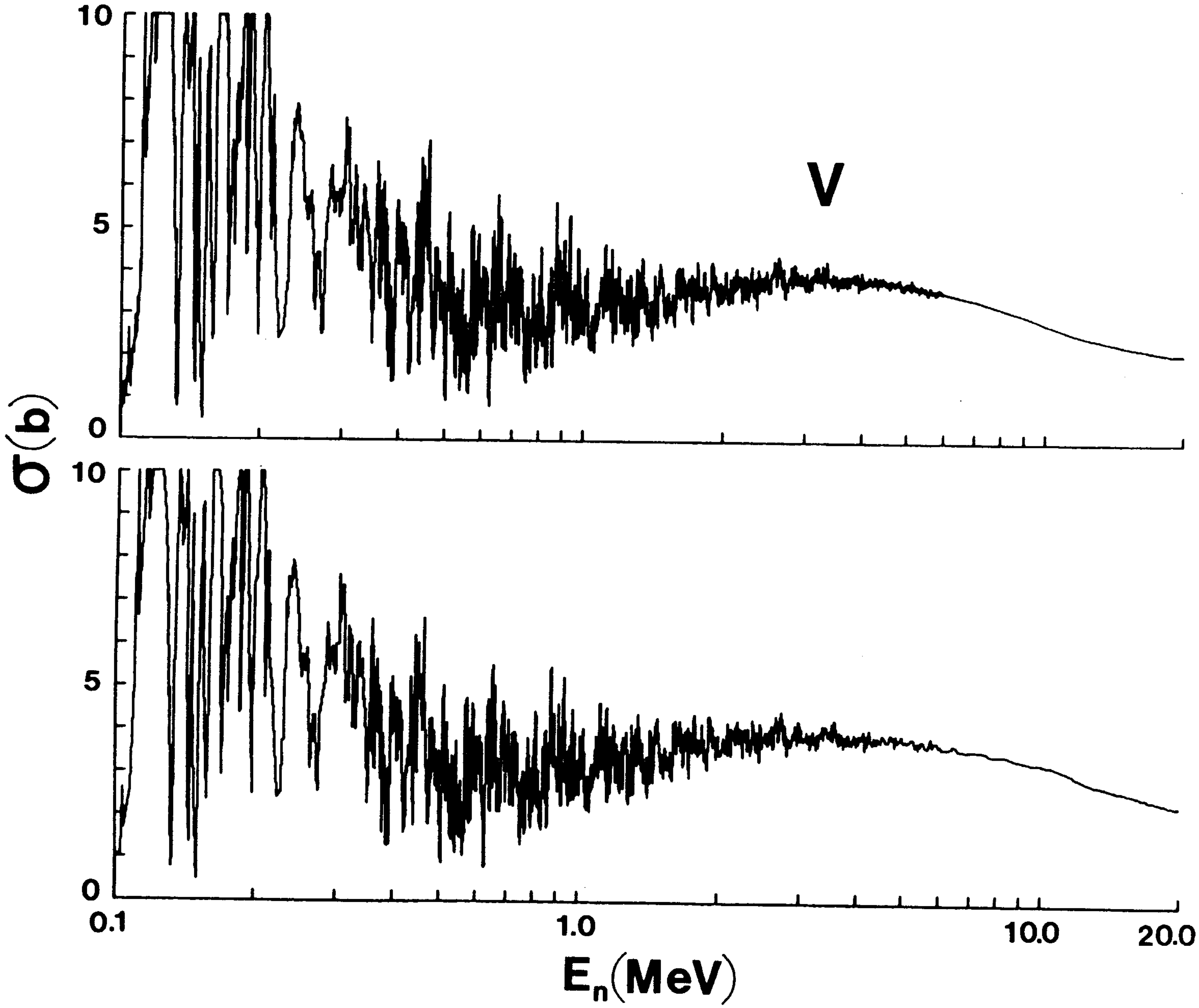

Fig. 3. The present evaluation above the resonance-parameter region (upper) and the comparable values given in ENDF/B-V (lower).

III. NEUTRON ELASTIC SCATTERING

The evaluated energy-averaged elastic-scattering cross sections were derived from the experimental and calculational studies of Ref. 33. In that work extensive measurements from 4.5 to 10.0 MeV are reported and discussed in the context of the entire relevant data base available from the National Nuclear Data Center[34] and as referenced in CINDA.[7] This data base consists of the experimental results of references 33 and 35 through 42. The experimental information above ≈ 11.0 MeV is confined to a single 14.7 MeV angular distribution,[20] with no other experimental information between ≈ 11.0 and 20.0 MeV. Therefore, considerable reliance had to be put upon model extrapolation from data below ≈11.0 MeV. The appropriate model is extensively discussed in Ref. 33. It well describes the measured elastic-scattering values, and concurrently provides a good description of the energy-averaged neutron total cross section from a few-hundred keV to 20.0 MeV, and of the ℓ = 0 strength function.

It is clear from an examination of the evaluated neutron total cross section that there are large fluctuations extending up to 5.0 or 6.0 MeV, and these will be enhanced in the single elastic-scattering exit channel. Such fluctuations are not consistent with a general optical model, nor are they shown in any detail in the experimental elastic-scattering data base. However, they do influence the experimental results, with considerable variation of the angular distributions for small changes in incident energy and/or the energy resolution used in the measurements. Since neither the model nor the measurements give any detailed knowledge of the fluctuations at these lower energies, the evaluation of the angular distributions is presented as an energy average, consistent with the optical model and the experimental evidence. The resulting evaluated angular distributions are illustrated in Fig. 4. They are very representative of the observations up to at least 11.0 MeV, as discussed in detail in Ref. 33, and are a reasonable extrapolation to the higher energies where there is no detailed observational information for comparison. All of these evaluated distributions are consistent with "Wick's Limit".[43]

Below ≈ 4.0 MeV, the evaluated angle-integrated, elastic-scattering cross sections were determined from the difference between the sum of the other partial cross sections and the total cross section. This procedure introduces all of the fluctuations of the latter in the elastic-scattering cross section, which is not exactly correct. However, the approach is a reasonable approximation, as the total cross section is very largely the elastic-scattering cross section in this lower-energy region. Furthermore, there is no other option, given the requirement of exact consistency between partial and total cross sections. Above ≈ 4.0 MeV the angle-integrated, energy-averaged elastic-scattering cross section was taken explicitly from the model of Ref. 33. This result, together with the evaluated total cross section, determines the non-elastic cross section. That non-elastic cross

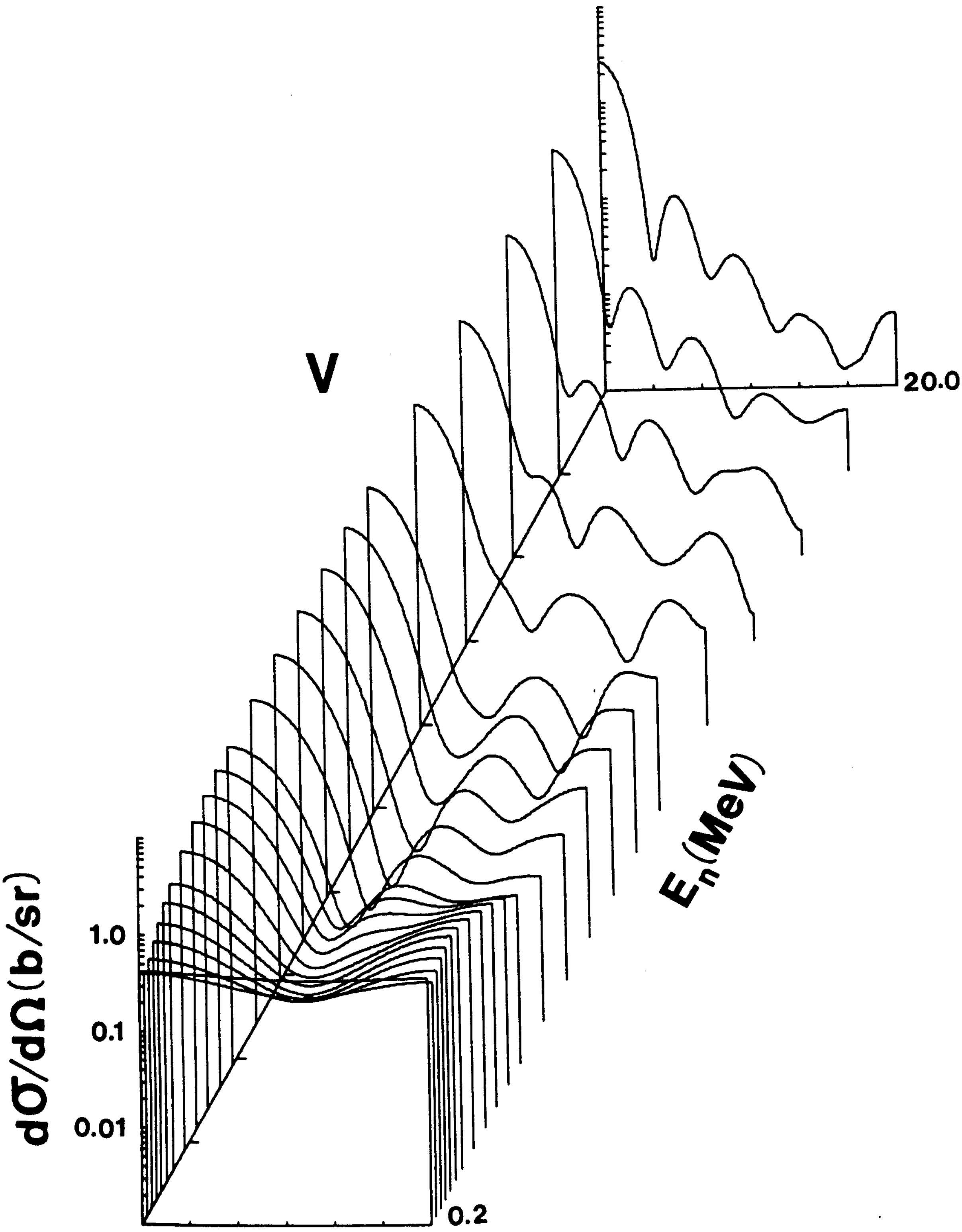

Fig. 4. Evaluated differential elastic-scattering cross sections of vanadium.

section is essentially constant from 10.0 to 20.0 MeV, as illustrated in Fig. 5. It is a governing factor in determining the continuum inelastic-scattering cross sections, as there are no direct measurements of the latter. Finally, the fluctuations of the total cross section are imposed upon the energy-averaged elastic-scattering cross section to 6.0 MeV, following the behavior of the total cross section.

The above elastic-scattering evaluation involves a complex mixture of models and measurements. The uncertainties, particularly of the former, cannot be quantitatively specified; thus, those associated with the evaluated result must be subjective estimates. They are judged to be 3-5% to 10.0 MeV, and 5% at higher energies in the angle-integrated energy-averaged values. The uncertainties associated with the angle-differential evaluated quantities are even more difficult to determine, but are probably of minor applied importance, as the elastic-scattering process is dominated by the single forward peak of the cross section, whose magnitude is largely determined by the angle-integrated values, and whose width is set by the angular location of the first-diffraction minimum. In view of these considerations, the evaluated file does not specify uncertainties for the angle-differential elastic-scattering values.

The present elastic-scattering evaluation is similar to that of ENDF/B-V[6,44] below ≈ 4.0 MeV (see Fig. 5). This is not surprising, as the data base at the lower energies has not significantly changed over the intervening years. However, above ≈ 4.0 MeV the present evaluated elastic-scattering cross sections are significantly lower than those of ENDF/B-V, by as much as 15-20% from 10.0 to 14.0 MeV. The recent experimental measurements strongly support the lower values.[33,38] The impact of these differences on the nonelastic cross sections is not as great due to the above-cited differences in the evaluated total cross sections.

In order to significantly improve the present elastic-scattering evaluation, more measurements are required. The entire evaluation above ≈ 11.0 MeV relies on a model extrapolation in a region where there is reason to believe that the model is undergoing some significant energy-dependent changes.[33,45] To provide improved definition, five to ten good differential-elastic-scattering measurements are required, distributed more or less uniformly between 12.0 and 25.0 MeV. At present there is essentially no information in this region. In the few-hundred keV region there is no direct experimental knowledge of the fluctuations in the elastic-scattering cross section. Very detailed measurements in this lower-energy region would be useful, but it would still be difficult to resolve energy-resolution and energy-scale differences between fluctuating total and elastic-scattering cross sections. Full representation of the fluctuating detail, if available, would require a considerable extension of the file content, and even the format.

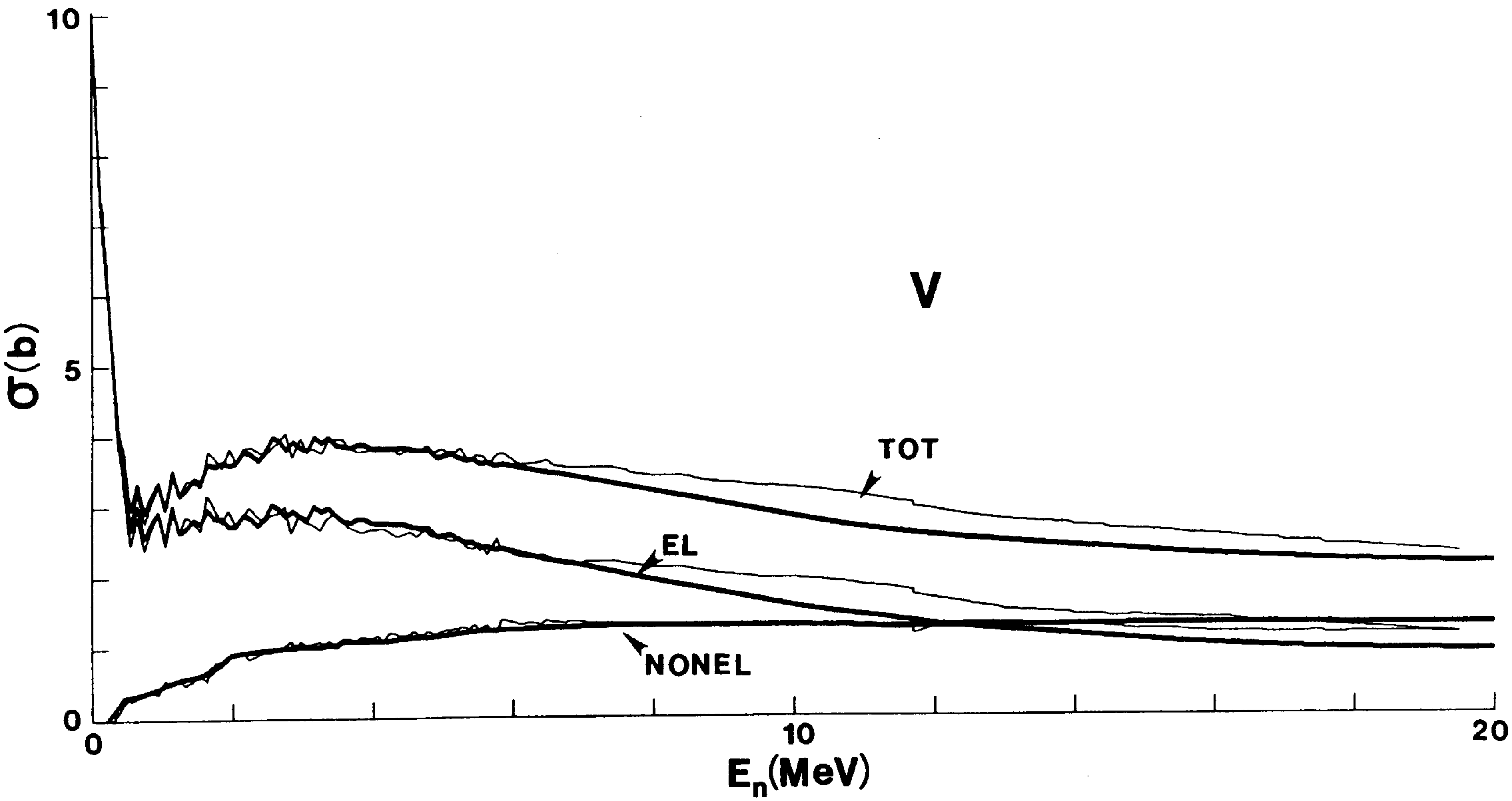

Fig. 5. Comparisons of the present energy-averaged evaluated total, elastic-scattering and nonelastic cross section of vanadium with those given in ENDF/B-V. Heavy curves indicate the present evaluation and light curves that of ENDF/B-V.

IV. NEUTRON INELASTIC SCATTERING

A. Discrete Inelastic Scattering

The discrete inelastic-scattering cross sections of this evaluation are the result of the excitation of twenty five levels. The excitation energies and J^{π} values, summarized in Table 2, are taken from Ref. 46. The relevant experimental data base are assembled from the files of the National Nuclear Data Center, from the literature, and from experimental work undertaken in explicit support of this evaluation. These experimental results are cited in Refs. 8, 33, 41, 42, and 47 to 54. More than half of the data were obtained using direct neutron-detection techniques, with the results relative to the H(n,n) or C(n,n) processes. Both of these standards are well known. Somewhat less than half of the experimental results were deduced from measurements of γ-rays emitted in the $(n;n',\gamma)$ process, using a variety of reference standards. Both types of results display considerable fluctuating structure at lower energies, illustrated by the work of Refs. 8 and 47. These fluctuations have been associated with doorway states.[47] Whatever their physical origin, they make it difficult to compare experimental results obtained at somewhat different energies and/or with different incident-energy resolutions. There is a general trend for the results obtained from $(n;n',\gamma)$ measurements to be systematically larger than those resulting from direct neutron measurements. Only the excitation of the first few levels is fully resolved by experiment, and above several MeV the observations result in composite cross sections due to contributions from the excitation of several levels. Most of the experimental results were obtained at incident energies $\lesssim$ 5.0 MeV. Only two sets of measurements extend to higher energies,[33,41] but they both strongly suggest that the inelastic scattering is largely a statistical process. The experimental data base is outlined in Fig. 6, where results obtained using (n,n') and $(n;n',\gamma)$ methods are indicated.

The evaluation makes no effort to follow the detailed fluctuations of the inelastic-scattering cross sections. The experimental definition is insufficient to do this, and theory can give only a qualitative statistical estimate of the fluctuations. The alternative is the energy-averaged representation. It was assumed that the inelastic-scattering cross sections are entirely due to compound-nucleus processes. With this assumption, the cross sections were calculated using the model and methods of Ref. 33, and the level specifications of Table 2. The calculated results were compared with the experimental data base, combining calculated excitations as necessary to make comparisons with the experimental values. The calculated results were then subjectively adjusted to improve the description of the measured cross sections. The normalizations were confined to the first few levels and were always less than 10%. In all cases the calculated energy-dependent shapes were retained. The evaluated results are compared with the experimental values in Fig. 6. The evaluated quantities are a good description of the experimental values, particularly of those obtained from (n,n') measurements.

Table 2. E_x and J^π values used in the compound-nucleus calculations.

Level No.	E_x(MeV)[46]	J^π values[46]
1	0.0 (g.s.)	$7/2^-$
2	0.320	$5/2^-$
3	0.929	$3/2^-$
4	1.609	$11/2^-$
5	1.813	$9/2^-$
6	2.411	$3/2^-$
7	2.547	$1/2^-$
8	2.677	$3/2^-$
9	2.699	$15/2^-$
10	3.085	$5/2^-$
11	3.150	$3/2^-$
12	3.195	$3/2^-$
13	3.215	$3/2^-$
14	3.264	$5/2^-$
15	3.280	$5/2^+$
16	3.372	$1/2^-$
17	3.377	$5/2^-$
18	3.378	$9/2^-$
19	3.381	$3/2^-$
20	3.383	$9/2^-$
21	3.386	$13/2^-$
22	3.396	$13/2^-$
23	3.444	$3/2^-$
24	3.445	$9/2^-$
25	3.454	$9/2^-$

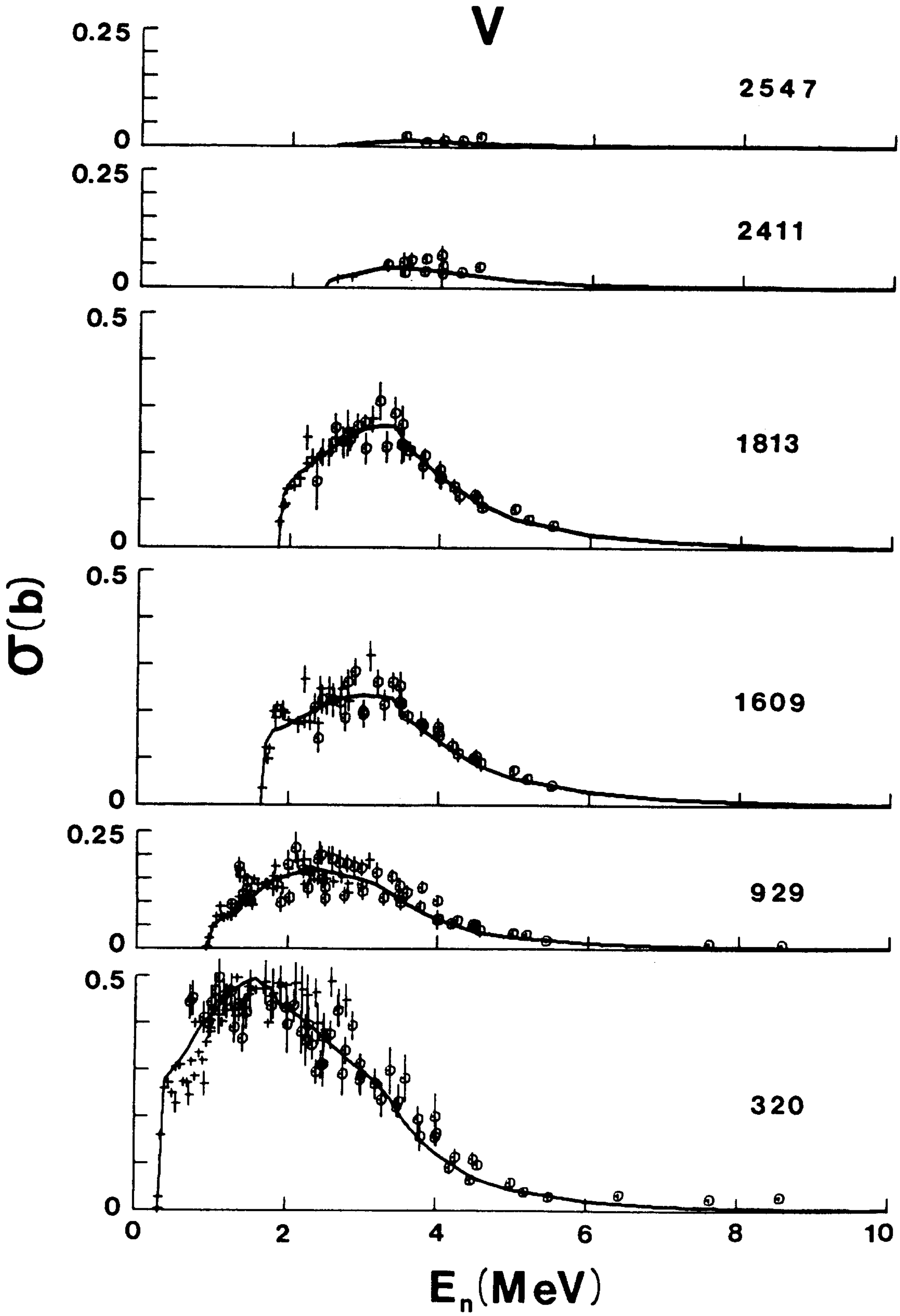

Fig. 6. Illustrative discrete inelastic-scattering cross sections of vanadium. Excitation energies are numerically cited in keV in each section of the figure. Curves indicate the present evaluation. The results of (n,n') measurements are indicated by "O" symbols, and those of (n;n',γ) measurements by "+" symbols.

The measurements and the calculations both indicate that the angular distributions of neutrons emitted as the result of the excitation of discrete levels are very close to isotropic in regions where the cross sections are of appreciable size. Therefore, the evaluation assumes isotropic emission associated with the discrete inelastic-scattering processes.

The cumulative sum of the evaluated discrete inelastic-scattering cross sections is shown in Fig. 7. This figure clearly indicates the onset of continuum inelastic scattering slightly above 3.5 MeV. The statistical level properties necessary for the calculation of competition from the continuum of levels are taken from Gilbert and Cameron,[55] as described in Ref. 33. The small artifacts in the cummulative sum of Fig. 6 are the consequence of the energy mesh employed in the evaluation. The present evaluation presents discrete inelastic scattering in much more detail than does ENDF/B-V; twenty-five excitation energies compared to seven. The sum of the present evaluated components is somewhat smaller than that of ENDF/B-V (for example, by ≈ 8% at 3.0 MeV), but the differences in the overall magnitudes are probably within the respective uncertainties. The latter are very difficult to estimate. However, a guideline is ≲ 10% uncertainty in the cumulative sum to incident energies of ≈ 3.5 MeV, with larger uncertainties at higher energies where competition from the continuum process is a significant factor.

New experimental results are necessary if the above evaluation is to be significantly improved. There are needs in two general measurement areas. In the lower-energy and fluctuating region, detailed measurements with at least intermediate resolutions are needed if the fluctuations are to be reasonably defined. Above ≈ 4.0 MeV the experimental information is sparse, and careful measurements will be needed for significant improvement. Both of these experimental areas represent major efforts. It is not clear that the present applied need warrants such efforts.

B. Continuum Inelastic Scattering

The integrated continuum inelastic-scattering cross sections were determined from the difference between the nonelastic cross sections and the other partial cross sections. The result is shown in Fig. 7. The magnitude of this cross section is probably known to ≈ 10%, in regions of appreciable magnitude, to 10.0 MeV. Above ≈ 10.0 MeV the (n;n,p) cross section becomes significant and it is not well known, as discussed in Section VIII. Its uncertainty, of perhaps 100 to 200 mb, will be correspondingly reflected in the continuum inelastic-scattering cross section above ≈ 11.0 MeV. Above ≈ 15.0 MeV there are relatively large uncertainties in the (n,2n) cross sections, as discussed in Section V. These, too, contribute to the uncertainties in the continuum-inelastic cross sections above ≈ 15.0 MeV. As a consequence, the continuum inelastic cross sections may not be known to better than 30% at 20.0 MeV. Fortunately, the continuum-inelastic uncertainties are largest above ≈ 15.0 MeV where there is little applied interest in the cross section. The evaluated continuum-inelastic cross sections are reasonably consistent with available experimental neutron-emission cross sections, as noted in Section X. They are also similar to those of ENDF/B-V in regions of appreciable magnitude, but somewhat smaller at 20.0 MeV. Generally, the differences between the two evaluations are within the respective uncertainties. The continuum-inelastic cross sections are reasonably measurable only below ≈ 10.0 MeV. However, significant experimental information does not exist in this region, and some good measurements should be made. Above ≈ 10.0 MeV, only composite neutron-emission cross sections can be experimentally determined, and these do not uniquely define this cross section. However, they are useful for testing the combined neutron-emission processes. Unfortunately, the experimental knowledge of the neutron-emission spectra at higher energies is limited, and thus several detailed measurements at selected energies are desirable.

The primary evaluation assumes isotropy in the continuum-inelastic-scattering, with the emission spectra described in Section X. This assumption is most suitable for the majority of processing codes now in applied use. The secondary evaluation gives a full angle-energy differential representation of the continuum-inelastic spectra.

V. (n,2n) AND (n,3n) PROCESSES

The (n,2n) Q-value is -11.051 MeV, and that of the (n,3n) reaction -20.385 MeV. Thus, only the former process need be considered in the present evaluation.

Measurement of the (n,2n) process in vanadium via conventional activation techniques is impossible as the product is stable (^{50}V). Therefore, the experimental information is obtained only using prompt-detection techniques, and it is sparse. Nearly three decades ago Ashby et al.[56] used a large liquid scintillator to measure a number of (n,2n) cross sections at an incident energy of ≈ 14.1 MeV. The detector efficiency was determined relative to ^{252}Cf nu-bar, and flux monitoring used the associated-particle method. The measurements appear to have been carefully done, but have not been corrected for experimental effects which are known to be significant in the application of this technique. More recently, Frehaut et al.[57] employed the same technique to make a wide range of (n,2n) and nu-bar measurements. They are carefully done, corrected using current knowledge, and generally have proven reliable. The Ref. 57 measurements of the (n,2n) cross sections extend from threshold to ≈ 15.0 MeV. There is a third set of data, reported by Auchampaugh et al.,[58] extending from ≈ 15.0 to 20.0 MeV. It too was obtained using a large scintillation tank. The data of Ref. 58 was reported as preliminary information only. Since they represent the only experimental evidence above ≈ 15 MeV, they are due some qualitative consideration. The above (very limited) experimental information is

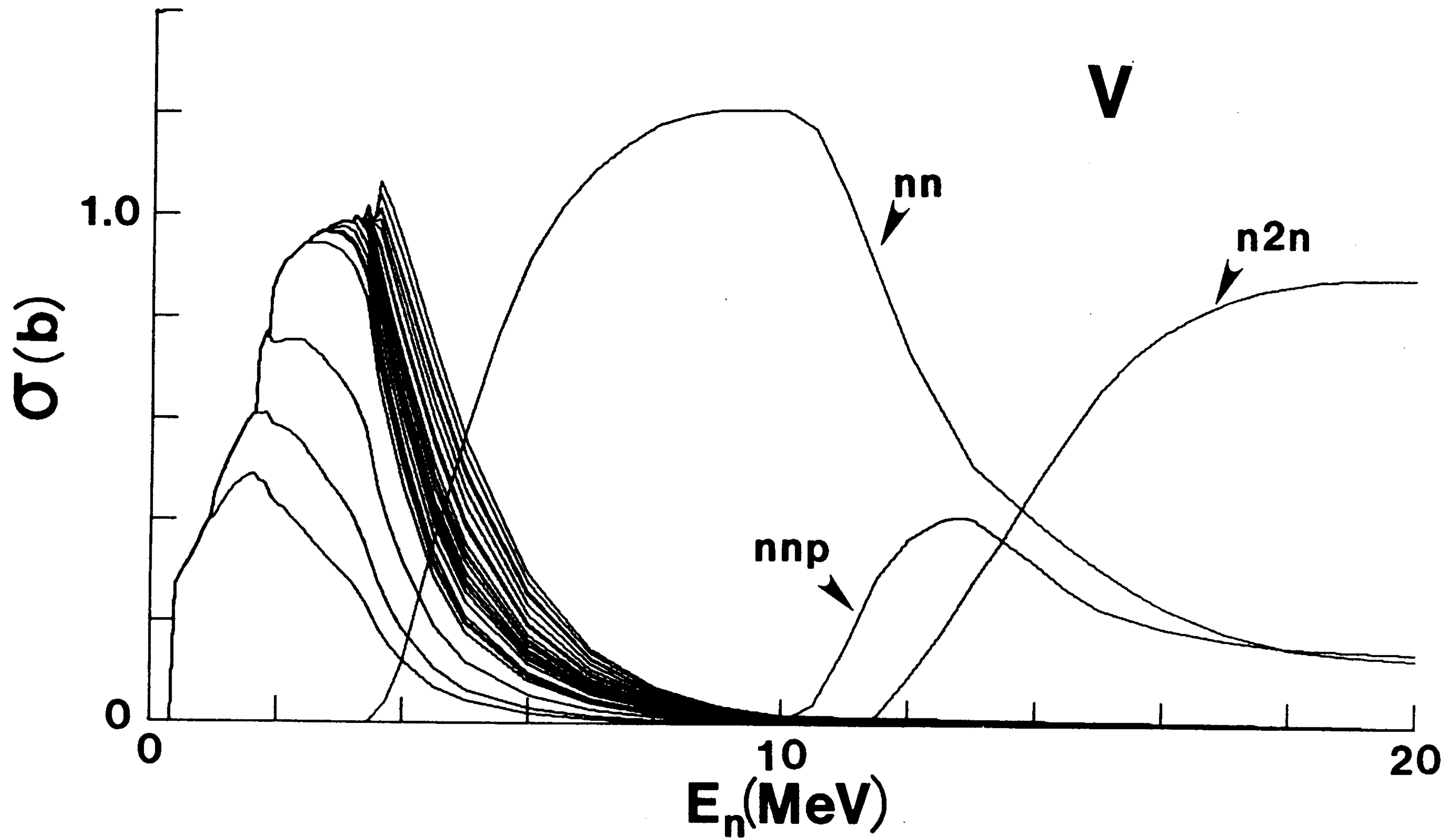

Fig. 7. The cummulative sum of the present evaluated discrete inelastic-scattering cross sections, compared with the evaluated continuum-inelastic, (n,2n) and (n;n,p) cross sections.

illustrated in Fig. 8. There is a discrepancy near 14.0 MeV between the results of Refs. 56 and 57. We have chosen to abandon the value of Ref. 56 due to its uncertain corrections, and the general reliability of the much later work of Ref. 57. Reference 57 then provides a relatively good data base to ≈ 15.0 MeV. The questionable results of Ref. 58 are ≈ 10% larger than those of Ref. 57 in the region of overlap near 15.0 MeV; however, they are the only experimental indication of energy dependence above 15.0 MeV.

Given the above experimental data base, there are considerable uncertainties above ≈ 15.0 MeV. Therefore, a calculational extrapolation to the region above 15.0 MeV was used for the evaluation. The calculations were carried out using the statistical-model code CADE of Wilmore and Hodgson[59]. These results displayed a relative energy-dependent shape that is very descriptive of the experimental information, but the magnitude is too large by ≈ 20% to 30%. Also, the neutron-emission spectra, described in Section X, indicate that the (n,2n) cross section continues to rise with energy above ≈ 14.0 MeV, in a manner consistent with the calculations. These various factors lead to the extrapolation of the cross section from 14.0 to 20.0 MeV shown by the curve in Fig. 8. This evaluation is fairly descriptive of what appear to be the more reliable lower-energy results.[57] In addition, it is reasonably consistent with the unconfirmed higher-energy values of Ref. 58.

The uncertainties associated with the above evaluation must be subjective estimates in view of the limited nature of the experimental data base. Guidelines are as follows:

E_n (MeV)	Uncertainty (%)
Threshold	25
11.5-12.0	15
12.0-15.0	9
15.0-18.0	15
18.0-20.0	20

The present evaluation is in very good agreement with that of ENDF/B-V up to 15.0 MeV. This is not surprising, as essentially the same data base is involved. Above 15.0 MeV the magnitude of the present evaluation is considerably greater than that of ENDF/B-V, largely because of the use of calculational models in the present work.

There is no direct experimental knowledge of the (n,2n) neutron-emission spectra, as it is impossible to explicitly measure them. Therefore, the (n,2n) emission-spectra determination relies primarily upon the model estimates described in Section X.

It will be difficult to improve upon this evaluation without significant new experimental information. In particular, measurements are needed in the very uncertain ≈ 15.0 to 20.0 MeV region. Some model improvement is perhaps possible, but probably not warranted until there is experimental information to test the calculational procedures.

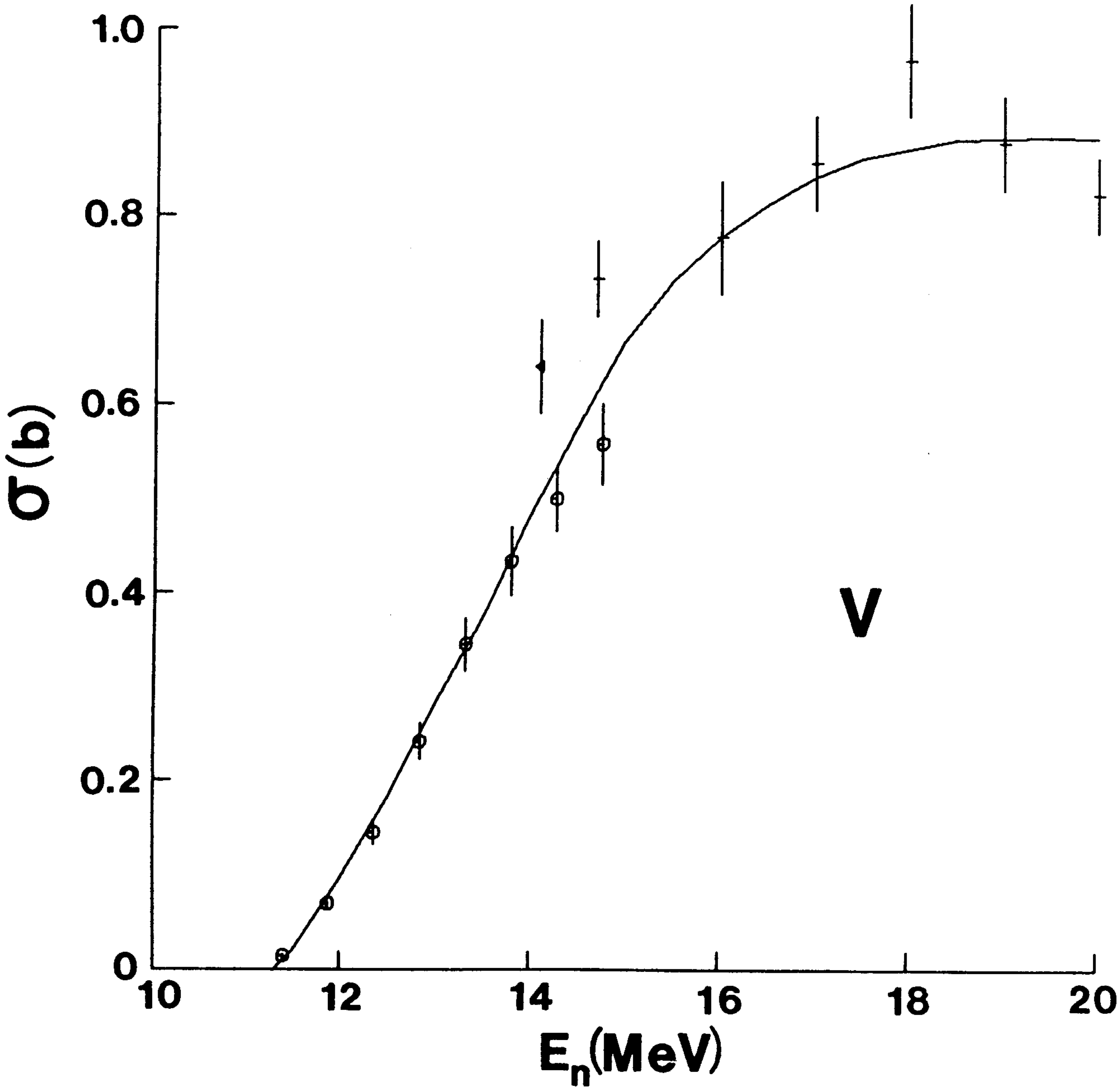

Fig. 8. Measured and evaluated (n,2n) cross sections of vanadium. The symbols indicate experimental results as follows: o = Ref. 57, ∇ = Ref. 56, and + = Ref.58 (renormalized as described in the text). The curve is the evaluated result.

VI. NEUTRON RADIATIVE-CAPTURE

Neutron capture in ^{51}V results in the 3.75 minute activity.[60] The decay of the product ^{52}V should be relatively easy to measure, thus determining, with flux monitoring, the capture cross section. The only apparent experimental obstacle is the relatively small size of the energy-averaged capture cross section. Despite this reasonable experimental potential, very little is known of energy-average capture cross sections of vanadium.

For the present evaluation, the experimental data base was assembled from the files of the National Nuclear Data Center and the literature, as referenced in CINDA.[7] This data base, given in references 61-96 and shown in Fig. 9, is sparse. The information is essentially all derived from some form of activity measurement. There are large discrepancies between some of the results, and, very frequently, uncertainties are either unspecified or appear to be rather optimistic. The data are best in the range ≈ 200 keV to 1.5 MeV, and that region was used for normalizing calculated values.

Given the less than definitive experimental situation, the present evaluation relies upon a statistical calculation using the dipole model, the code ABAREX,[97] the optical-model potential of reference 98, and the adjustment of the $\ell = 0$ strength function to give a subjectively-judged description of the energy-averaged behavior of the experimental values over the range ≈ 200 keV to 1.5 MeV. The calculation describes only the compound-nucleus process, so a small direct-capture component is added at high energies. Its magnitude is guided by the measured ≈ 14 MeV values, ignoring the larger values which are likely to be distorted by lower-energy neutron capture. From the neutronic point of view, the addition of the high-energy component is hardly more than a cosmetic effect, since the cross sections never exceed 1 mb in this region.

The evaluation is descriptive of the general trends of the experimental results and is similar to the prior ENDF/B-V evaluation[44] (see Fig. 9). The similarity of the two evaluations is not surprising, as there has been little, if any, change in the fragmentary experimental data base. Substantive improvements will require some careful, but feasible, new measurements. These could well use rather broad incident-neutron-energy resolutions and conventional activation techniques. The cross sections are small; thus, the measurements will be tedious, however the half-life is short. The uncertainties associated with the present evaluation are, of course, relatively large and qualitative (e.g., ≈20% from 0.2 to 1.5 MeV, and larger at other energies). The saving grace, for most applications, is the very small magnitude of the capture cross section throughout the energy-average region.

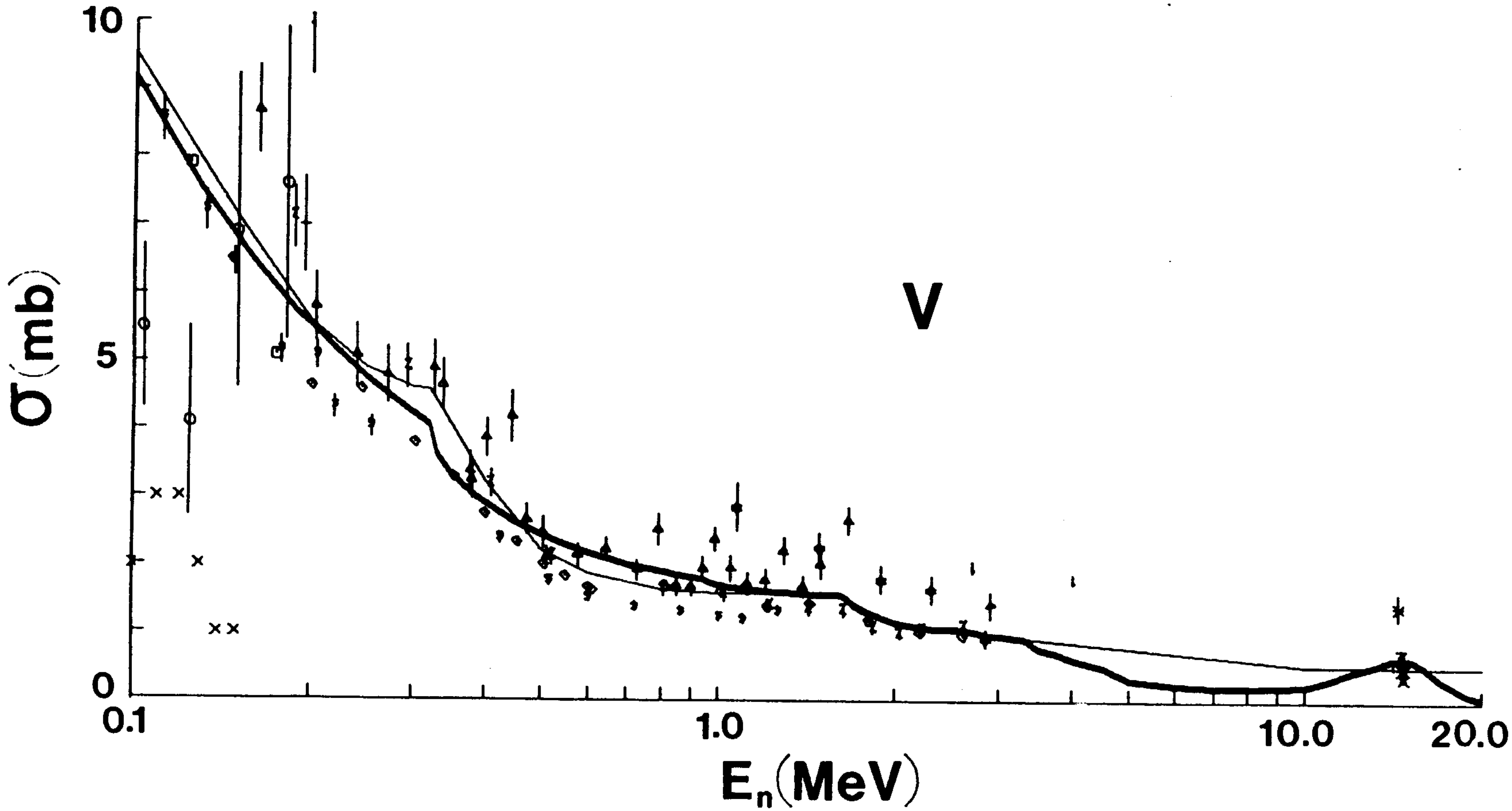

Fig. 9. Radiative capture cross sections of vanadium. The symbols indicate the experimental data base; the heavy curve, the present evaluation, and the light curve, that of ENDF/B-V.

VII. THE (n,α) AND (n;n',α) PROCESSES

A. The (n,α) Process

The Q-value of -2.055 is relatively low[99] and the process is readily accessible to activation measurements. As a consequence, there is a reasonable body of experimental data available. The relevant data were assembled from the files of the National Nuclear Data Center and the literature, as cited in Refs. 69 and 100 to 128. The data sets were plotted on a large scale and inspected. A number of the experimental results appeared discrepant with respect to the main body of the information (as noted among Refs. 69 and 100-128 and illustrated in Fig. 10), and these were abandoned. Generally, the measurements were made relative to a standard, frequently the Al(n,α) reaction or the ^{235}U or ^{239}U fission cross sections. The older measurements often lacked specification, and assessment of the respective standards and/or the experimental method was a matter of archeology that was not attempted. The newer measurements (resulting in the body of accepted information) were generally relative to ENDF/B-V standards. The latter were accepted for this evaluation, as the ENDF/B-VI standards were not yet available. This is probably not a serious shortcoming, as the applicable ENDF/B-V and -VI standards are expected to be very similar. In view of the above, the data were accepted as published without attempting to renormalize to a particular set of standards. This procedure may, in a few cases, lead to anomalous results, but there should not be a significant perturbation of the evaluation result.

The uncertainty specifications vary widely from data set to data set, ranging from none to statistical uncertainties only, and to, in a few cases, full specification of both statistical and systematic uncertainties. Very little knowledge of possible correlations is available. Given this situation, a considerable amount of subjective judgement was involved in establishing uncertainties. An attempt was made to perform the evaluation using the statistical evaluation program GMA.[2] This analysis was performed using seventeen grid-point energies, distributed between 6.0 and 20.0 MeV. The results obtained from this analysis exhibit serious statistical anomalies attributed to the limited data base, but they do provide an estimate of the relative uncertainties for the various energy regions. Furthermore, these results, exclusive of the statistical anomalies, do not differ systematically from the smooth curve proposed by Kanno et al.[130] The uncertainties provided by the GMA code appeared to be too small in an absolute sense, particularly in comparison with the results of Evain et al.[129] in the vicinity of 14.0 MeV. The version of GMA used does not provide a χ^2 test for consistency, so the overall uncertainties were increased to obtain reasonable consistency with the the well-supported error estimate of Evain et al.[129] The resulting uncertainties are listed in Table 3. Since the correlations obtained from the GMA solution were quite small, it was decided to ignore them entirely and to treat the estimated uncertainties as uncorrelated.

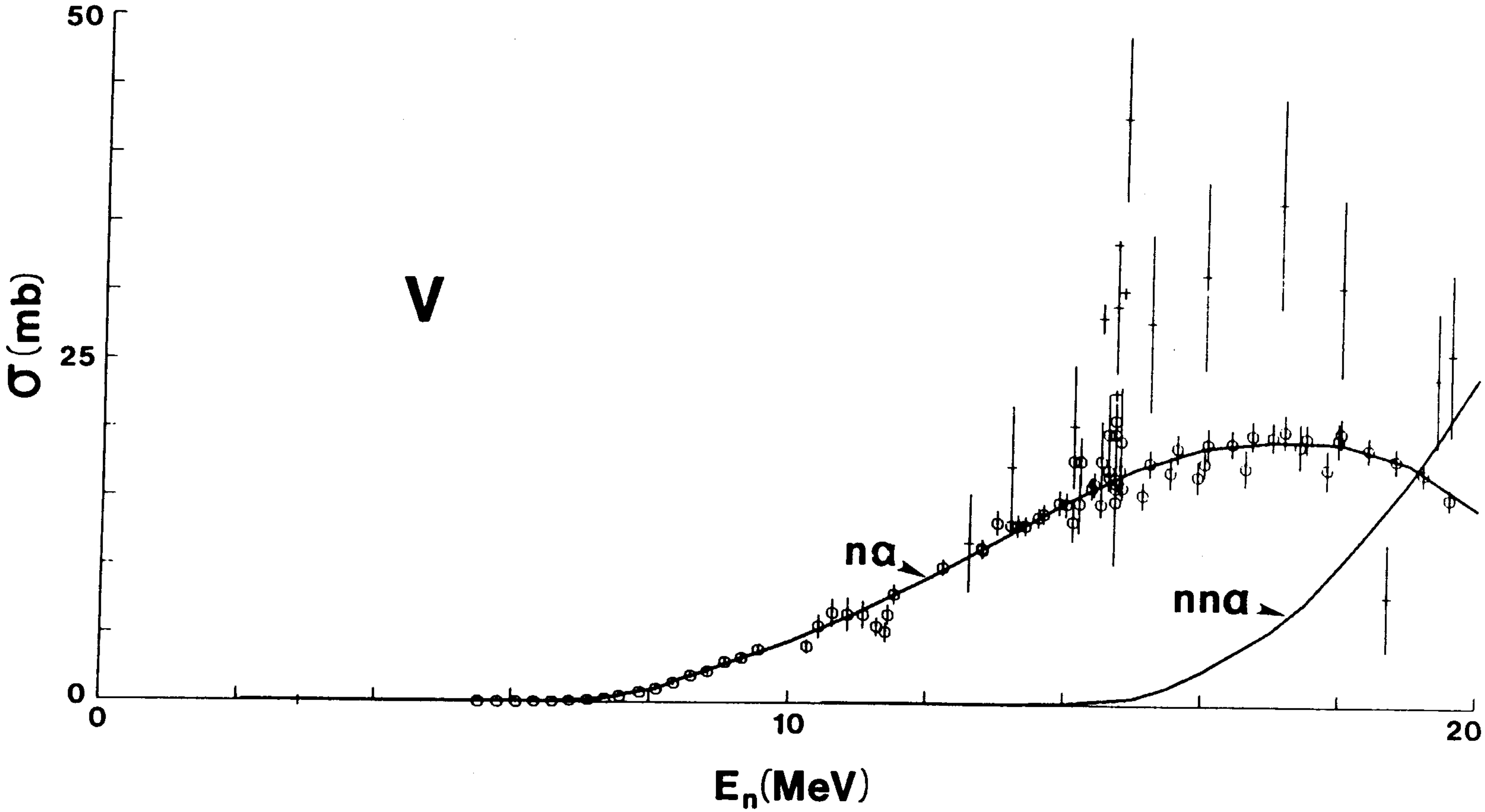

Fig. 10. Measured and evaluated (n,α) and (n;n',α + α,n') cross sections. Measured (n,α) values are indicated by "O" (accepted for evaluation) and "+" (omitted from evaluation). Curves indicate the evaluated results.

Table 3. Evaluation Uncertainties

E_n (MeV)	Uncertainty (%)
<6.0	>15.0
6.0	13.0
6.4	10.0
7.6	9.0
8.0	8.0
8.4	7.0
9.0	8.0
12.0	6.0
14.0	3.0
15.0	6.0
16.0	8.0
18.0	10.0
20.0	10.0

The (n,α) cross sections were calculated, assuming statistical processes, using the code CADE.[59] The calculated result had an energy-dependent shape similar to that of the present evaluation, but the maximum was ≈ 30% larger in magnitude. In particular, the calculation indicated that the (n;α,n') reaction was very small below ≈ 14.0 MeV, and that there was no gross structure in the cross section. Therefore, the fluctuations in the data in the 10.0 to 12.0 MeV region were attributed to experimental artifacts rather than true physical behavior.

The present evaluation is ≈ 25% smaller in magnitude at the maximum than that of ENDF/B-V,[44] and it does not show the gross structure of ENDF/B-V at ≈ 10.0 MeV. These differences are not surprising, as ENDF/B-V did not benefit from the wealth of recent experimental information available for the present evaluation. Also, the present evaluation gives a much better definition of the threshold region, as illustrated in Fig. 11, again due to recent experimental information.[106] At 14.7 MeV the present evaluation is 4.5% larger than the evaluation of Ref. 129. This difference is within the respective evaluation uncertainties, and again reflects the effect of new experimental information (e.g., that of Refs. 108 and 130). The present evaluation is very similar to the cross sections recommended in Ref. 130. The latter reference includes some careful comparisons with measured integral properties, with good agreement between the differential and integral results. Since the present evaluation and the cross sections of Ref. 130 are so similar, this evaluation is also very consistent with the results of integral measurements.

The present (n,α) evaluation appears to be relatively well known. Significant improvements will require a number of careful new measurements. The smaller values (relative to ENDF/B-V) may be of concern as they imply significant reductions in helium production at energies of applied interest.

B. The (n;n'α) and (n;α,n') Processes

The threshold for these processes is relatively high (Q = -10.294 MeV[99]). The sum of the cross sections was set equal to the difference between the total α-production cross section and the above (n;α,γ) cross section. The total α-production cross section was determined by calculation,[99] and was then normalized to the above evaluation below 12.0 MeV. The calculated (n;α,n') cross sections are much larger than the (n;n',α) values up to 20.0 MeV. There are several experimental results near 14.0 MeV;[101,105,110,118,131] all were obtained using activation techniques. They generally indicate an upper limit of the cross section at this energy of several mb or less. Calculations indicate that above ≈ 16.0 MeV the cross section rises rapidly, and this behavior is supported by the experimental results of Ref. 132 and the higher-energy (above 20.0 MeV) measured value of Ref. 120. The resulting evaluated cross section is shown in Fig. 10. The evaluation is reasonably consistent with the experimental values. However, it is

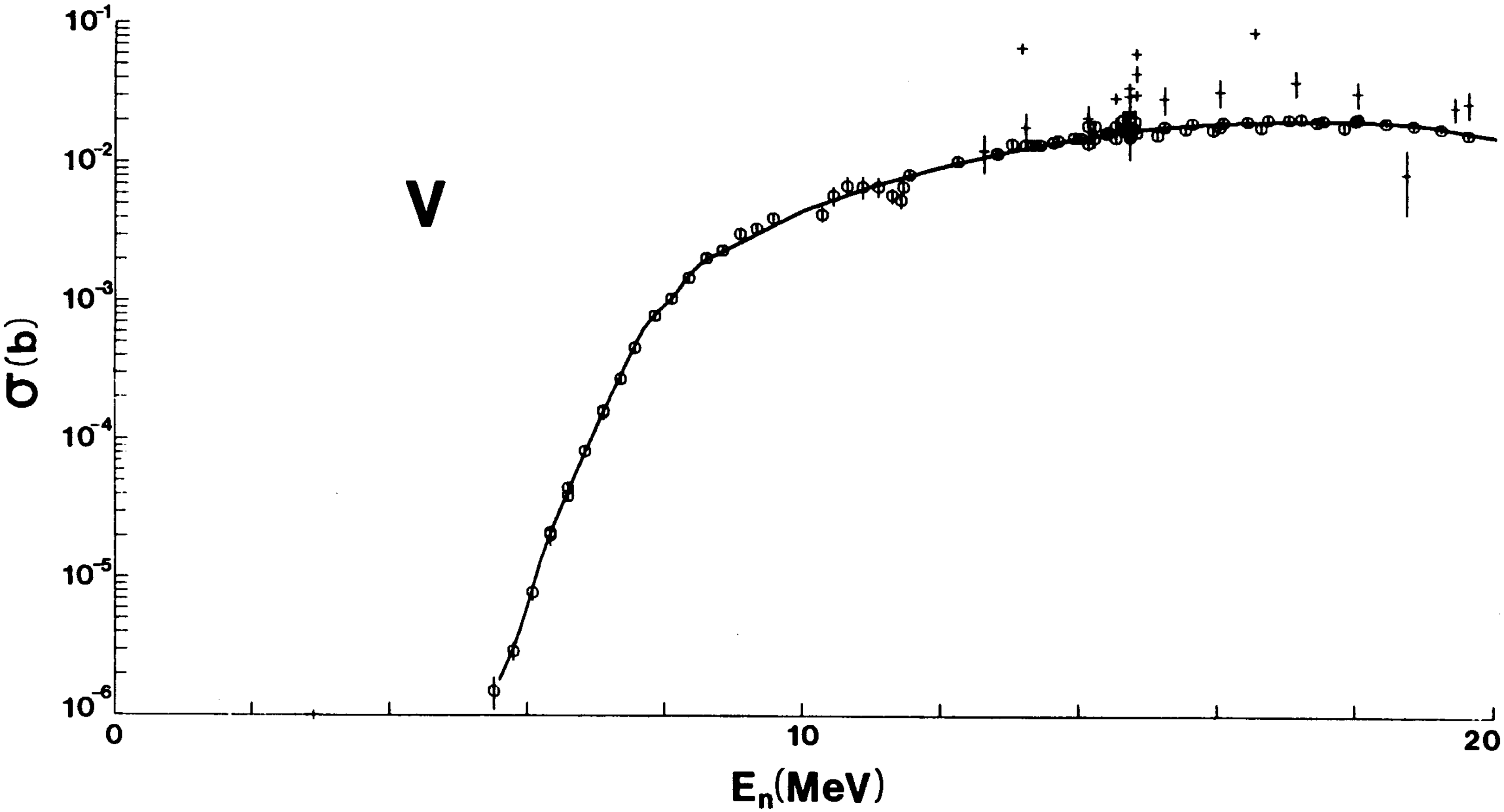

Fig. 11. Measured and evaluated (n,α) cross sections. The notation is identical to that of Fig. 10. The semilog plot emphasizes details of recent measurements.[130]

relatively uncertain (e.g., by 10-20% at 20.0 MeV). This uncertainty will persist until better experimental data are available. It may not be a concern in most applications, as the cross section is very small at energies of interest to fusion- and fission-energy development.

The evaluation describes the emitted neutron spectrum by means of model calculations, as described in Section X. There are considerable uncertainties in this method, but they will be of little applied concern due to the very small magnitude of the relevant cross section.

VIII. (n,p) AND (n;n',p) PROCESSES

A. The (n,p) Process

The Q-value of the reaction is -1.684 MeV[39], and the production of the residual ^{51}Ti product is readily measured with activation techniques. Despite the relative ease of the measurement, the experimental data are not particularly plentiful, consisting of the works of Refs. 133 to 149. These data can be grouped into three categories: i) the extensive measurements of Ref. 133, ranging from near threshold to ≈ 10.0 MeV, ii) a single set of measurements extending to 20.0 MeV,[149] and iii) a number of experimental results at ≈ 14.5 MeV. Thus, aside from the 14.0 MeV region, the evaluation must rely on only two relatively comprehensive data sets.[133,149] This limited data base does not lend itself to statistical evaluation methods; thus, a subjective approach was taken.

The initial step was an examination of the ≈ 14.0 MeV region. The relevant data scatter by more than a factor of two. However, the newer results (those obtained during approximately the past decade) are fairly consistent and have small uncertainties. These were generally accepted for the evaluation, and results of a qualitatively different magnitude (largely much older results) were abandoned. The selection is noted in Refs. 133 to 149. Some of the large differences in the data may be due to the use of different reference standards. However, it is difficult to make an assessment of the standards used in many of the older results, and even if done, the relatively large uncertainties would have little impact on the evaluation. The newer (and generally accepted) data largely postdate ENDF/B-V and thus generally employed ENDF/B-V standards. ENDF/B-VI standards were not available at the time of the present evaluation, but it is doubtful that their use would significantly change the evaluated result. Near 14.5 MeV, the cross section is essentially energy independent. Thus, for the present evaluation, a weighted average of the accepted experimental values near 14.5 MeV was constructed using the uncertainties cited by the original authors. The result was a cross section of 28.6 (± ≈ 5%) mb at 14.5 MeV. This value is ≈ 10% smaller than that given in the evaluation of Ref. 128 due to the introduction of new experimental results which are generally lower than the body of information available for the evaluation of Ref. 128. Even so, the two evaluated results are very nearly consistent within their respective cited uncertainties.

Below ≈ 13.0 MeV there is only one set of experimental data.[133] It is extensive and is in good agreement with the predictions of statistical-model calculations.[89] Thus this set of data, complemented by model calculations to interpolate the shape from 10.0 to 14.0 MeV, was used to determine the evaluation below the 14.5 MeV region. There is only one set of data above ≈ 14.5 MeV,[149] and it extends from ≈ 13.0 to 20.0 MeV. However, its magnitude is 10-15% larger than the above-evaluated ≈ 14.5 MeV result. Moreover, the same authors, in a companion study of the (n,α) reaction, obtained results that were again higher than those indicated in the present evaluation (see Section VII). Therefore, the normalization of this set of data is suspect. Statistical calculations lead to results that are much smaller than the observed values above ≈ 12.0 MeV.[89] Pre-compound contributions to this process must be significant at the higher energies. Calculations combining statistical and pre-compound processes[150] support such a contention and give an energy-dependent shape of the cross section similar to that reported from the experiments of Ref. 149, though the calculated magnitudes are larger than all experimental results, and increasingly so as the energy decreases. With these calculational and experimental results, the evaluation simply uses the measured values of Ref. 27 above ≈ 14.5 MeV, normalized to the evaluated 14.5 MeV result outlined above. The resulting evaluation is compared with the experimental data base in Fig. 12. A similar comparison in Fig. 13 more clearly defines the threshold region.

In view of the subjective nature of the above evaluation, uncertainty guidelines are suggested as follows:

E_n (MeV)	Uncertainty (%)
< 4.0	≥ 10
8.0	10
10.0	8
14.0	5
16.0	10
20.0	12

Above ≈ 10.0 MeV, the present evaluation is systematically smaller than that of ENDF/B-V[44] by ≈ 25%, and below 10.0 MeV, there are considerable differences in both shape and magnitude. These differences are due to the new and much better data available for the present evaluation. Cross section guidelines are set forth in Ref. 133. They are 20-30% larger than the present evaluation, again reflecting new and improved experimental data not available for the work of Ref. 133. Reference 133 makes some comparisons between differential and fission-spectrum-averaged cross sections. For ^{235}U, the differential data suggested in Ref. 133 imply results ≈ 22% larger than obtained in fission-spectrum-averaged measurements.[151,152] The present evaluation and the suggested data of Ref. 133 have approximately the same values at

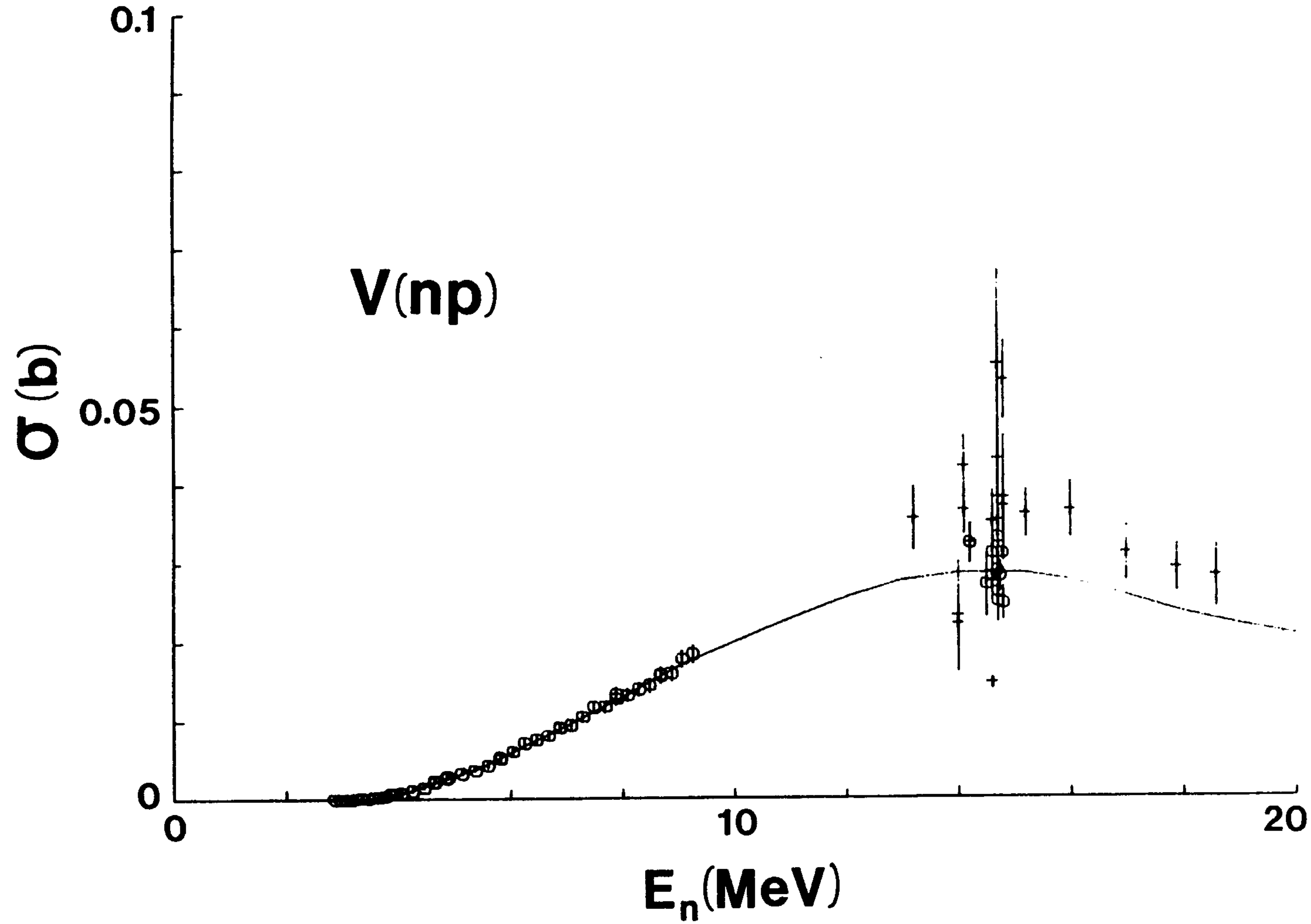

Fig. 12. Comparison of measured (symbols) and evaluated (curve) (n,p) cross sections. The "O" symbols denote results used in the evaluation, "+" those not used in the evaluation.

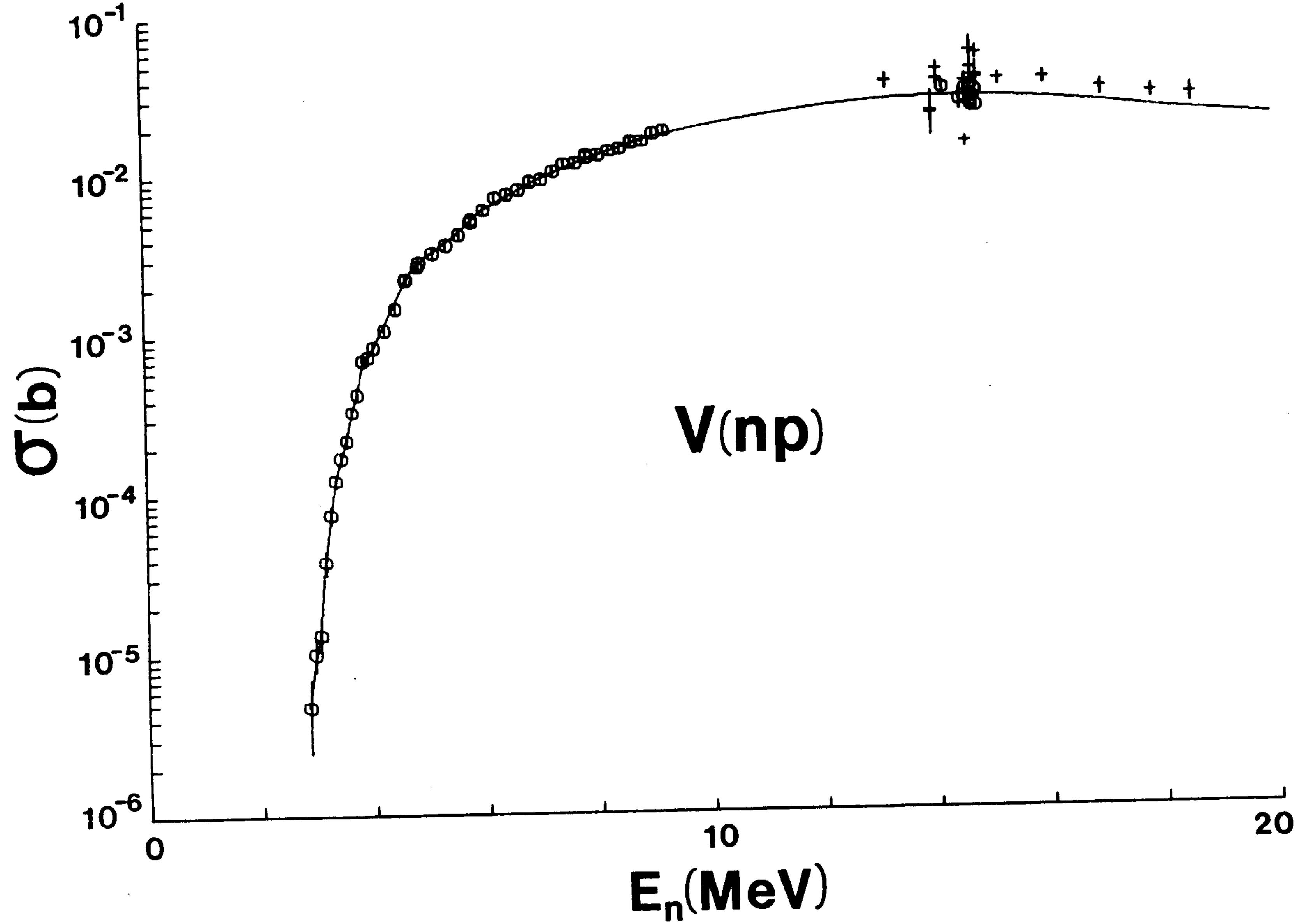

Fig. 13. Logarithmic comparison of measured and evaluated (n,p) cross sections. The notation is identical to that of Fig. 12. Semilog plot emphasizes details provided by new measurements.[133]

the lower energies which govern the fission-spectrum-averaged results; thus, the difference between integral and differential ^{235}U spectral-averaged results cited in Ref. 133 will persist with the present evaluation. Reference 133 also makes comparisons with the results of ^{252}Cf fission-spectrum-averaged measurements. The latter are a bit disturbing, as they are much larger than those for ^{235}U, by a factor of more than two in one case.

Significant improvement in the present evaluation will require extensive new experimental information. Several sets of dependable experimental results are needed in the 15.0 to 20.0 MeV range. At present, there appears to be no reliably normalized data for this region. Below ≈ 12.0 MeV the evaluation rests entirely on a single data set. It is of wide energy scope and is believed to be reliable. However, it should be verified with several independent and accurate measurements.

B. The (n;n',p + p,n') Processes

There is apparently no relevant experimental information for these processes (Q = -8.057 MeV).[99] Therefore, the evaluation must rely entirely on calculational estimates. Calculations were made using the Wiesskopf-Ewing statistical model,[59] and using that model with the addition of pre-compound contributions.[150] The two calculated results agree very well at ≈ 20.0 MeV (i.e., σ = ≈ 143 mb). However, near threshold the calculations differ by large amounts, with the statistical result being the larger. The concurrent statistical-calculation results for the (n,p) cross section are in good agreement with the experimental values to ≈ 12.0 MeV, and gave a qualitatively reasonable description of the (n,2n) cross section. The evaluation makes a compromise between the two types of calculated results, adjusted to give a reasonable neutron-emission spectrum, as discussed in Section X. The evaluation is characterized by relatively large values near threshold, falling to much smaller values with the onset of the (n,2n) cross section. Near threshold, the (n;n',p) process is the larger contribution to the total process. The corresponding neutron-emission spectra are discussed in Section X. The latter are approximations but are judged to be suitable in view of the large uncertainties associated with the cross section itself. It is impossible to quantify the cross-section uncertainty with any degree of reliability, but it is at least 25% over much of the energy range.

The present evaluation is considerably larger (factors of 5 or more near threshold) than that of ENDF/B-V and has a different energy-dependent shape. These differences are the consequences of using different models, the results of which are all more than a little speculative. The evaluation cannot be improved without significantly better models, and the latter will require experimental verification.

The corresponding measurements will be very difficult, as the residual product is stable, and its formation cannot be separated from that due to the (n,d) process. The alternative of direct proton-emission measurements is difficult, and the experimental results are not clearly separable from the (n,p) process.

IX. OTHER PARTICLE-EMITTING REACTIONS

A. The (n,d) and (n;n'd + d,n') Processes

The reaction product for the (n,d) process (Q = -5.832 MeV)[99] is stable ^{50}Ti. Thus there is only fragmentary experimental information based upon direct deuteron-detection measurements.[153,154,155,156] These experimental results suggest a cross section in the range 5-10 mb in the 14.0 to 15.0 MeV region. The most careful measurement appears to be that of Ref. 153, where the deuteron production cross section at 15.0 MeV is given to be ≈ 7.0 mb. The evaluation uses the results of statistical calculations,[59] normalized to the experimental value of Ref. 153 at 15.0 MeV. The normalization factor is 3.6. The resulting evaluation is quite similar to that of ENDF/B-V, but both are uncertain by 25% or more, particularly away from the 15.0 MeV region. The threshold of the (n;n',d + d,n') is very high (Q = -16.776 MeV),[99] and statistical calculations suggest cross sections of far less than 1 mb, even at 20.0 MeV. The evaluation explicitly uses the results from these statistical calculations, and assumes angle-isotropic temperature distributions for describing the emitted neutrons. The results are very uncertain, perhaps by 100% or more, but, due to the high threshold and the small magnitudes, that uncertainty is of little concern in most applications.

B. The (n,t) and (n;n't + t,n') Processes

The cross sections for the (n,t) reaction were calculated using the statistical model.[59] There are only very fragmentary experimental values available for comparison. At ≈ 20.0 MeV the calculations indicate a cross section of ≈ 0.48 mb, which is reasonably consistent with the experimental 30.0 MeV value of 0.55 mb given in Ref. 157. Reference 158 suggests a value of the order of 1 mb at ≈ 14.0 MeV, which is somewhat larger than the calculated result. The present evaluation uses the calculated results and is approximately an order of magnitude smaller than the comparable evaluation of ENDF/B-V. Calculations indicate that the (n;n't + t,n') cross section is less than 1 μb at 20.0 MeV. Moreover, the threshold for the reaction is very high (above 19.0 MeV); thus, the process was ignored in the present evaluation.

C. The (n,^{3}He) and (n;n',^{3}He + ^{3}He,n') Processes

The fragmentary experimental evidence for the (n,^{3}He) reaction suggests that the cross section is less than 1 mb at ≈ 14.0 MeV.[159,160] Again, the evaluation is based upon statistical-model calculations.[59] The result is smaller than given in ENDF/B-V, but the uncertainties associated with both evaluations are very large. For neutronic applications, this cross section is of no concern. The threshold for the (n;n',^{3}He + ^{3}He,n') reaction is above the upper-energy limit of the evaluation; thus, the process was ignored.

D. The (n;α,p +p,α) Process

This process is included in the evaluation for completeness. The cross sections were calculated using the statistical model,[59] and they are in the few μb range at the most. They are of no interest in neutronic applications.

E. The (n;2p) Process

Again, this process was included in the evaluation for completeness, using statistical-model[59] calculations to provide numerical values. The cross sections are only a few μb at most and thus are of no interest in neutronic applications.

X. CONTINUUM NEUTRON-EMISSION SPECTRA

The continuum neutron-emission spectra are made up of contributions from the (n,n'), (n;2n'), (n;n',p + p,n') and (n;n',α + α,n') reactions (the small (n;n',d + d,n') component is separately handled as described above). The individual components can be directly observed experimentally over the majority of the energy range; where only the sum of the contributions can be measured. The primary evaluation presents the spectra in the File-5 format which does not include any angular information. The more detailed angle-energy differential representation of File-6 is used in the secondary version of the evaluation, and it will be described elsewhere. The following remarks outline the derivation of the primary File-5 formulation of the evaluation.

The individual reaction spectra were calculated using the computer codes ALICE[161] and CADE.[162] ALICE calculates reaction cross sections and the spectra of the emitted particles. As used, it employed the hybrid model for pre-compound processes, the Weisskopf-Ewing evaporation model for compound decay. It does not include a gamma-ray channel. CADE performs compound nucleus calculations by the Weisskopf-Ewing formalism. The level density formalism and parameters are those of Brancazio and Cameron.[163] Gamma-ray emission is described by the giant dipole resonance formalism. For simplification it was assumed that the pre-compound process only involves the emission of a single nucleon. This seems to be a fairly good assumption up to 20 MeV, where multiparticle pre-compound emission is only a few percent of the total reaction cross section. According to the model calculations, all the possible reactions that involve the emission of three particles have very small cross sections, so they are ignored.

For this evaluation ALICE was used to calculate neutron spectra, while CADE was used to divide the components among the several reactions. The spectrum of emitted neutrons in the (n,n') continuum reaction is given by

$$S_{n,n'}(E_{in},E) = D_{n_1}(E_{in},E)\ P_{n_1,\gamma}(E_{in} - E),$$

where E_{in} is the energy deposited by the incident neutron, E is the energy of the relative motion of the emitted neutron, $(E_{in} - E)$ is the excitation energy of the residual nucleus after the emission of one neutron, $D_{n_1}(E_{in},E)$ is the distribution of the energy of the relative motion for the neutron when it is the first particle emitted, and $P_{n_1,\gamma}$ is the probability that the residual nucleus decays by γ-emission (leading to the (n,n') reaction). Since it is assumed that no reaction involving three emitted particles is possible, the expression for the (n;2n') neutron spectrum is

$$S_{n,2n'}(E_{in},E) = D_{n_1}(E_{in},E)\ P_{n_2}(E_{in} - E) + D_{n_2}(E_{in},E),$$

where $P_{n_2}(E_{in} - E)$ is the probability that a second neutron is emitted and D_{n_2} is the distribution in energy of the second neutron. Similar expressions can be written for the (n;n',p) and (n;n',α) reactions. ALICE was used to calculate the D_n terms for the above equations, and CADE was used to calculate the P_n terms.

The initial approach used only the computer code ALICE. However, at incident neutron energies above 10.0 or 12.0 MeV, the partial cross sections calculated with ALICE did not sum to the total reaction cross section. At about 15.0 MeV the difference was several hundred mb. A detailed examination of the results suggested that ALICE was underestimating the branch of the (n;n',p) reaction proceeding through an initial neutron emission by rather large amounts. In the particular case of ^{51}V, the (n;n',p) branch is expected to have an unusually large cross section because the initial emission of a neutron leaves an excited ^{51}V nucleus where the neutron separation energy is about 3.0 MeV greater than that of the proton and alpha. There is a 3.0 MeV range of excitation energy where the emission of a second neutron is not energetically possible. However, alpha particle emission is not competitive at these energies, and gamma-ray emission is only competitive for excitation energies of 1.0 MeV or less. Thus, there is a region of excitation energy about 2.0 MeV wide where only proton emission is effectively possible. At energies a few MeV above the reaction threshold, this 2.0 MeV wide band can amount to a substantial fraction of the total reaction cross section. Calculations using the statistical model code CADE gave the expected behavior for the (n;n',p) branch, but it did not include the contributions from the precompound process. ALICE seemed to give reasonable spectra for the emitted particles so it was used for that purpose, and CADE was used to determine how the spectra were to be apportioned among the several reactions.

The differences between the calculated total reaction cross sections and those in the above evaluation are generally less than 10%, and they could probably be removed by adjustment of optical-model and other parameters used in the calculations. Such adjustments were not attempted, as the effect on the desired emission spectra is expected to be small. Otherwise, the calculated cross sections for the various reactions are in qualitative agreement with those independently deduced in the evaluation outlined above.

The calculated spectra were transformed to the laboratory system, maintaining energy correlation but assuming no angle correlation. Added together, the components, weighted with the respective cross sections, give total emission spectra that are qualitatively consistent with those observed experimentally.[164] The calculated emission spectra have small artifacts due to non-exact meshing of the various components in regions of rapidly changing cross section. They should have no applied significance. However, consideration of the shape of the resulting total emission spectra offered guidance as to the evaluated cross sections in regions where there is no experimental information. This is particularly true of the (n;2n') and (n;n',p) cross sections, where the emission spectra (and underlying calculations) strongly suggest the rise of the former with energy above ≈ 15.0 MeV (see Fig. 8), and the magnitude of the peak of the latter (see Fig. 7) with significant effect on the continuum (n,n') cross section above ≈ 15.0 MeV.

For completeness, spectra are given at the threshold energy for each reaction. Ideally, these spectra should be δ-functions at energies corresponding to the motion of the center-of-mass. However, δ-functions are hard to represent in a tabular form, so they are represented by triangles with a 100.0 eV base.

The above spectra are considerably different from those given in ENDF/B-V. In particular, the energy distributions of the individual components display sharp energy dependencies, due to the changes in channel configurations of a nature that are not found in ENDF/B-V, which was an empirical construction. The differences between the overall emission spectra derived from the two evaluations are not as pronounced. As noted above, it is not experimentally possible to measure these individual emission spectra, but some high resolution measurements of the total emission spectra would be useful, particularly as they might indicate a pronounced direct-reaction peak at the upper energy of the spectra due to direct excitation of low-lying states or clumps of states.

XI. PHOTON PRODUCTION

The photon-production data are made up of contributons from the (n,γ), $(n;n',\gamma)$, and a continuum from all other photon-producing reactions.

Photon production for the (n,γ) reaction is dealt with by providing an energy-dependent photon multiplicity and spectra. The spectrum of photons from the neutron-capture reaction was taken from the work of Orphan et al.[165] at thermal neutron energy. The average energy of the spectrum was determined and divided in the Q-value for the reaction in order to provide the low-energy photon multiplicity. The same spectrum was used at 20.0 MeV, with the multiplicity adjusted to conserve energy.

For the photons associated with inelastic scattering to specific levels, Warren's code, CASCADE,[166] which incorporates the method used in Reffo's BRANCH[167] code, was used to obtain the energy-dependent cross sections for specific photons resulting from the de-excitation of the levels excited by inelastic neutron scattering.

For the other reactions, the photon-production cross sections and spectra were calculated using the R-parameter formalism of Perkins et al.[168] The R-parameter formalism requires formal representation of energy distributions for all secondary particles, charged particles as well as neutrons, in order to calculate the photon-production cross sections and spectra. Since the ENDF/B-VI formats and procedures allow for secondary charged-particle distributions in File 5 only if there is a single secondary particle, the file was translated to the ENDL format, where energy distributions for all secondaries can be represented. The R(U) values used were derived from the work of Newman and Morgan,[169] since the mass of vanadium is at the lower bound of the validity of the "global" R(U) values used for heavier elements.

After entering the calculated photon-production data into the file, energy conservation was calculated and was verified to within 5% for all incident energies of the file.

XII. SUMMARY

A comprehensive evaluated neutronic data file for vanadium is described, including evaluation methodology, computational methods, and experimental data bases. The primary version of the evaluation assumes isotropy of nonelastic neutron emission, and a secondary version includes the angle-energy correlation of neutron emission (additional documentation elsewhere will describe angle-energy correlations). The primary version will be directly applicable in a wide range of established processing codes. The main objective of the evaluation is the provision of neutronic data for the development of fission- and fusion-energy systems, particularly those having relatively hard neutron spectra.

The present evaluation is considerably different from that of ENDF/B-V in a number of areas, due largely to new experimental information. Specifically:

a) Resonance parameters are included in the evaluation.

b) Total cross sections of the present evaluation are up to 10% smaller in the ≈ 7.0 to 16.0 MeV range.

c) The present evaluated elastic-scattering cross sections are 15% to 20% lower in the 10.0 to 14.0 range, an important feature for fusion-energy considerations.

d) The discrete inelastic-scattering cross sections are somewhat lower and are given in more detail.

e) Above ≈ 15.0 MeV, the present (n,2n') cross section becomes increasingly larger with energy.

f) The (n,α) cross sections are smaller by ≈ 25%.

g) The (n,p) cross sections are lower by ≈ 25%, and the structure of ENDF/B-V is not reproduced.

h) The continuum emission spectra are different, particularly in the context of the individual components.

Whether or not these changes are of concern will depend upon the application and the desired accuracy of the neutronic calculations.

In order to significantly improve the present evaluation, new measurements are needed. These include:

1) Detailed resonance measurements and interpretations to ≈ 500 keV. The 200 to 400 keV region is particularly important.

2) Precise differential elastic-scattering measurements at approximately five incident energies from 10.0 to 20.0 MeV.

3) Careful determinations of the continuum neutron-emission spectrum at several incident energies distributed between 8.0 and 20.0 MeV.

4) Precise (i.e., to within 5%) measurements of the (n,2n') cross section at several energies between 14.0 and 20.0 MeV.

5) Broad-resolution measurements of the capture cross section from ≈ 50 to 2000 keV. Activation techniques should be suitable.

6) Measurements of the (n,p) cross section from ≈ 10.0 to 20.0 MeV to ≈ 5% accuracy. Activation techniques should be suitable.

7) A few, very high-resolution neutron-emission measurements at selected incident energies would assist in defining the contributions of the various components to overall emission spectrum.

In addition to the above measurements, attention should be given to vehicles for model extrapolation, well validated against experimental information.

Finally, it should again be emphasized that this evaluation is for general neutronic applications. Those interested in specific applications (e.g., dosimetry, activities, etc.) are encouraged to consult specialized files tailored toward those objectives.

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