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ANL/NDM-107

An Evaluated Neutronic File for Elemental Cobalt

by

P. Guenther, R. Lawson, J. Meadows, M. Sugimoto,
A. Smith, D. Smith, and R. Howerton

August 1988

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

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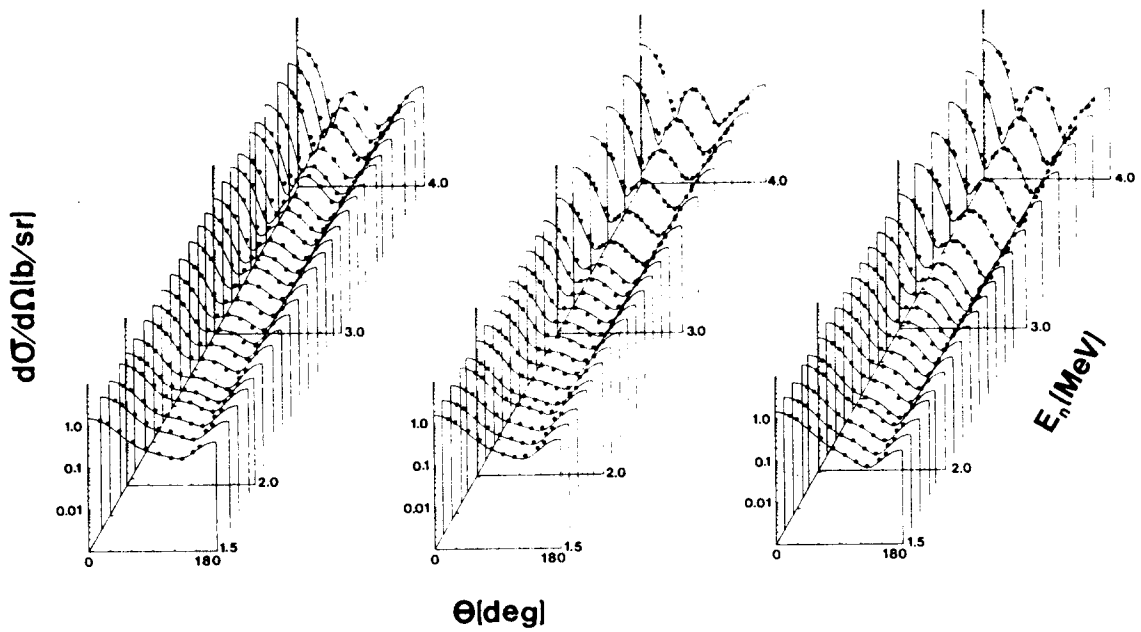

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ANL/NDM-107

AN EVALUATED NEUTRONIC DATA FILE FOR ELEMENTAL COBALT*

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P. Guenther, R. Lawson, J. Meadows, M. Sugimoto**,
A. Smith and D. Smith
Argonne National Laboratory

and

R. Howerton
Lawrence Livermore National Laboratory

August 1988

Keywords

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Applied Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439
U. S. A.

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** Permanent address, Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan

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P. Guenther, R. Lawson, J. Meadows, M. Sugimoto**,
A.B. Smith and D.L. Smith
Argonne National Laboratory

and

R. Howerton
Lawrence Livermore National Laboratory

ABSTRACT

A comprehensive evaluated neutronic data file for elemental cobalt is described. The experimental data base, the calculational methods, the evaluation techniques and judgments, and the physical content are outlined. The file contains: i) neutron total and scattering cross sections and associated properties, ii) (n,2n) and (n,3n) processes, iii) neutron radiative capture processes, iv) charged-particle-emission processes, and v) photon-production processes. The file extends from 10^{-5} eV to 20 MeV, and is presented in the ENDF/B-VI format. Detailed attention is given to the uncertainties and correlations associated with the prominent neutron-induced processes. The numerical contents of the file have been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory.

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** Permanent address: Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan.

I. INTRODUCTION

This document outlines the physical considerations, the evaluation methods and judgments, and the content of an evaluated neutronic data file for elemental cobalt. The primary objective of the file is a quantitative microscopic neutronic data base for fission- and fusion-energy applications. All processes of neutronic concern in such applications are included in the file. Particular attention is given to dosimetry-related cross sections, as elemental cobalt is readily available and provides good dosimetry energy coverage with a single sample through (n,γ) (low-energy), (n,p) and (n,α) (moderate-energy), and (n,2n) (high-energy) reactions. Specialized applications may need ancillary data that are not included in this file (e.g., certain photon-decay activities). Special-purpose files should be addressed in these cases. The file is primarily based upon experimental information obtained from the microscopic data files of the National Nuclear Data Center,[1] gathered from the literature, and obtained in a complementary measurement program explicitly motivated by this file.[2] Theoretical calculations were used to interpolate between measured quantities, and to extrapolate to unmeasured (or unmeasurable) values where necessary. The complementary work of Ref. 2 gives very careful attention to establishing the fundamental nuclear models underlying most of these calculations. Where the experimental data base was sufficiently detailed, rigorous statistical evaluation methods were employed.[3] These methods provided a good specification of uncertainties and correlations.

The file has been subjected to routine clerical and physical checks for accuracy. The file is presented in the ENDF/B-VI system format. Two versions are given. The first assumes isotropy of continuum-inelastic-scattering neutron emission. In so doing, this version of the file is fully consistent with the majority of processing codes now in operation. In the second version, the angle-energy correlation of the neutrons emitted in the continuum-inelastic process is defined. That detail is not needed for many applications and is not consistent with the large majority of contemporary processing codes. This document explicitly addresses the first form of the file. A supplemental document will provide such additional definition as is requisite for the second version of the file. The file has been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. Interested parties can obtain the corresponding numerical values from that Center, or from the authors. Requests to the authors should include BITNET addresses.

Subsequent sections of this document deal with specific portions of the file.

II. TOTAL CROSS SECTIONS

The essential envelope of an evaluated neutronic file is a precisely known neutron total cross section as, in the ENDF system, all partial cross sections must conform to it. Furthermore, some portions of the file are

essentially determined by the nonelastic cross section, the derivation of which requires a well-determined total cross section. As a result of the ENDF requirement for rigorous cross-section consistency, errors in the evaluated total cross section will certainly be propagated to other portions of the file. Certain physical checks (e.g., Wick's Limit) are no more valid than the total cross section. Of all the cross sections, only the total cross section can be measured in a self-normalizing manner, independent of a reference standard. Despite this simplicity, the total cross sections are often not as well known as they should be, as there are persistent experimental perturbations and ambiguities due to experimental resolutions and other causes. In view of the key importance of the total cross section, it was given considerable attention in the present evaluation.

A. Resonance Parameters

The present evaluation uses the resonance parameters of Mughabghab[4] with modifications of Dunford and Mughabghab[5] to describe the neutron elastic-scattering and capture cross sections up to incident neutron energies of 100 keV. A small background was introduced to assure continuity at the matching energy. The neutron elastic-scattering and radiative-capture cross sections were constructed from the resonance parameters, using the computer code RECENT.[6] Of course, these combine to provide the neutron total cross sections, which were compared with the totality of the experimental data available from Ref. 1, regardless of experimental conditions. The agreement was reasonably good, given the wide variation in experimental results, as illustrated in Fig. 1. The present resonance results are qualitatively similar to those of ENDF/B-V, as the experimental data base has not greatly changed in the intervening years, but they benefit from the improved interpretation of Ref. 4.

B. Energy-averaged Neutron Total Cross Sections

A comprehensive experimental neutron-total-cross-section data base was assembled from the literature as referenced in CINDA,[7] and as available from the files of the NNDC.[1] This data base was augmented with values obtained from i) measurements undertaken by the authors,[2] ii) independent literature searches, and iii) particularly, from the results of comprehensive measurements by Harvey,[8] explicitly carried out for this evaluation. The experimental data base extends from the resonance region (100 keV) to 20 MeV. The individual data sets are cited in Refs. 9-33. As noted in the references, not all of these data sets were accepted for the evaluation due to obvious abnormalities and/or inappropriate energy ranges. The lower-energy data sets strongly fluctuated with energy due to prominent resonance structure observed with varying degrees of experimental resolution. The resolution and scope of Ref. 8 generally appears to be superior. In order to smooth fluctuations and obtain a reasonable energy-averaged representation, the individual data sets were energy averaged, using ≈ 100 keV energy intervals at the lowest energies and increasing to ≈ 500 keV at 20.0 MeV. These averaging increments were a compromise, smoothing most of the fluctuations yet retaining the general energy dependence of the cross

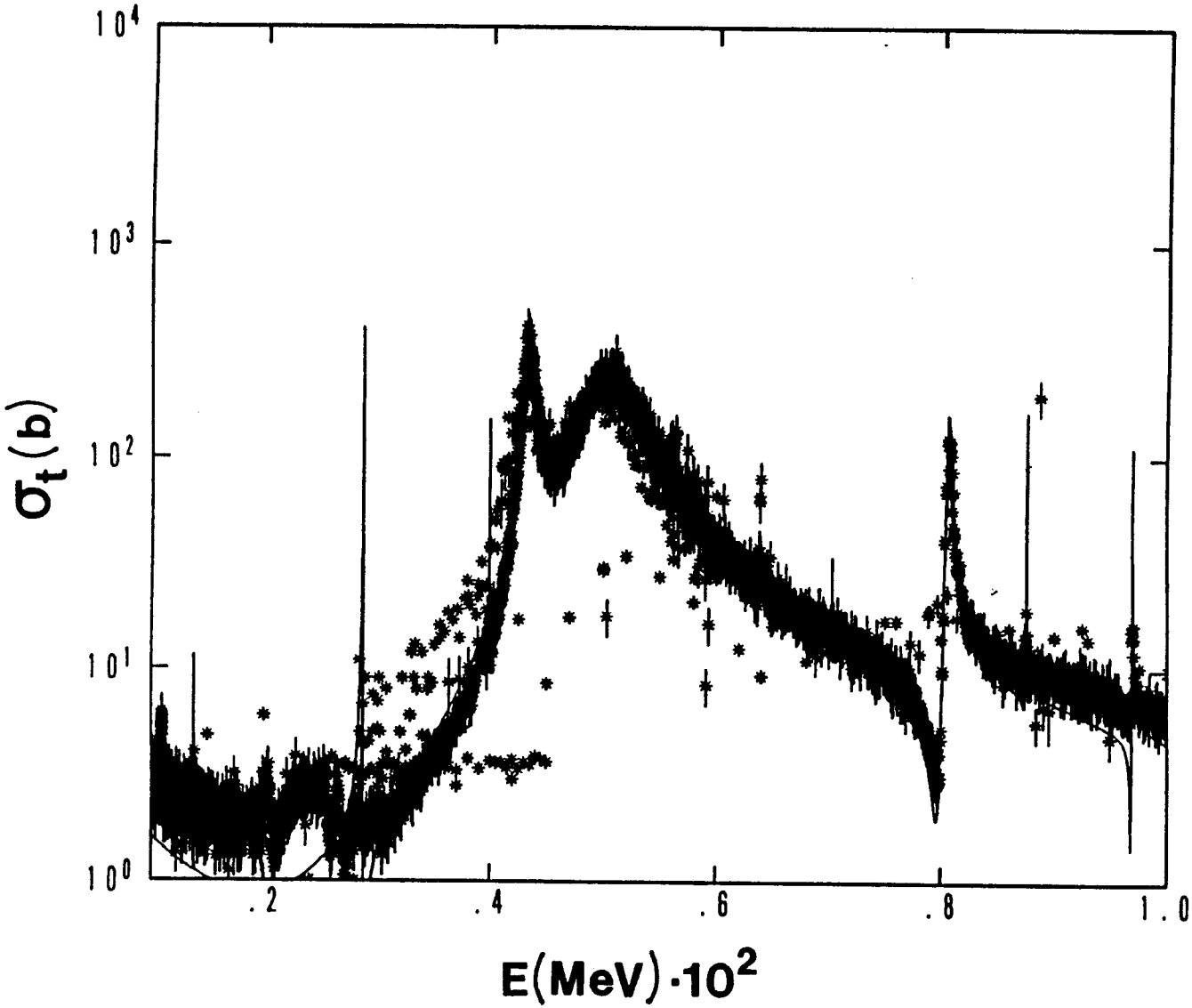

Fig. 1. Illustrative comparisons of the evaluated resonance region (curve) with the totality of experimental results available from Ref. 1 (symbols), irrespective of experimental conditions or quality.

section. The fluctuations persisted to some extent at the lower energies, even in these averaged values. The individual energy-averaged data sets were inspected using large scale plots, and obviously erroneous data sets and/or datum values were deleted from the data base. Generally, the cross sections were deduced from conventional transmission measurements,[3,4] and thus the results were actually "effective" cross sections, meaningful only within the context of the samples and resolutions used in the particular measurements. In particular, at lower energies the experimental results may have been distorted by self-shielding effects that are very difficult, if not impossible, to assess from the published information. The consequence is that the energy-averaged values may be systematically distorted towards too low values by several percent in a number of cases. The distortions will be largest for those experimental results obtained with the thicker samples and lesser resolutions. Qualitatively, the distortion is probably not serious, as i) the effect was carefully assessed in Ref. 2 and found to be negligible above 1.0 MeV, and ii) several sample sizes were used in the very good resolution results of Ref. 8 with generally consistent energy-averaged results, both within the data set and with respect to a number of other data sets.

For nearly all of the data sets, only statistical uncertainties were quoted. These were generally small, particularly in the energy-average, and did not account for some of the qualitative discrepancies between various data sets. In the absence of quantitative information, systematic uncertainties were estimated using subjective judgments. These judgments included consideration of other concurrently measured values, particularly a reference standard such as carbon. The statistical and systematic uncertainties were propagated through the evaluation procedure, as outlined below. The complete energy-averaged data base used in the evaluation is outlined in Fig. 2.

The evaluation was constructed from the above energy-averaged data base using the statistical processing code GMA.[3] That code rigorously constructs the best evaluated data set to a predetermined mesh from the experimental data base, and provides the associated evaluation uncertainties and covariance matrix. The uncertainties are, of course, a reflection of the subjectively judged systematic uncertainties cited above, and therefore should be used for qualitative guidance rather than quantitative definition. The resulting evaluation uncertainties are small (fractional percent) and may well be an unduly optimistic estimate resulting from the statistical interpretation. Subjectively more realistic values are probably a factor of 2-3 larger, particularly above ≈ 15.0 MeV where the evaluation essentially entirely relies upon a single data set. Therefore, the uncertainties resulting from GMA were increased by a factor of two to assure conservative estimates. They are given, in a relatively wide energy mesh, in Table 1. It should be stressed that these uncertainties are relevant only to the energy-averaged evaluated cross section, and not to the details of the resonance fluctuations introduced as described below. The covariance matrix, again on a relatively coarse energy mesh, is given in Table 2.

The above statistically derived evaluated-data set displayed small fluctuations due to variations in the underlying experimental data. These

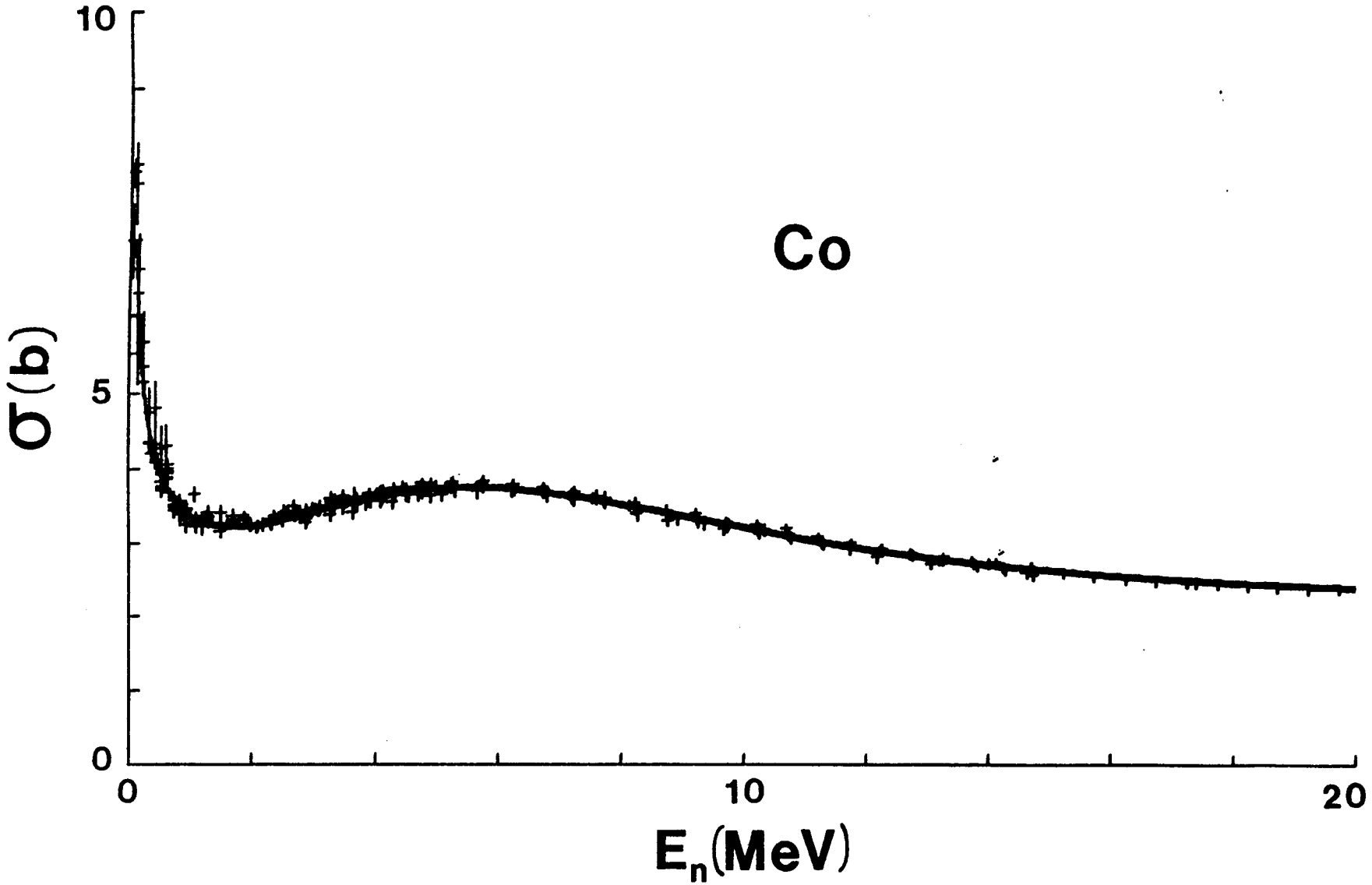

Fig. 2. The energy-averaged experimental total cross section data base (symbols) and the present energy-averaged evaluation (curve).

Table 1. Energy-averaged evaluation uncertainties as a function of energy.

Energy (MeV)	Uncertainty (%)
0.1	1.4
0.2	0.4
0.3	0.4
0.4	0.4
0.5	0.4
0.6	0.4
0.8	0.4
1.0	0.4
1.2	0.4
1.4	0.4
1.6	0.4
1.8	0.4
2.0	0.4
2.2	0.6
2.4	0.6
2.6	0.4
2.8	0.4
3.0	0.6
3.5	0.4
4.0	0.4
4.5	0.4
5.0	0.4
5.5	0.4
6.0	0.6
6.5	0.6
7.0	0.6
7.5	0.6
8.0	0.6
8.5	1.0
9.0	0.6
10.0	0.6
11.0	0.6
12.0	0.6
13.0	0.6
14.0	0.6
16.0	0.8
18.0	0.8
20.0	1.0

Table 2. Correlation matrix of the energy-averaged evaluation, using a coarse energy mesh.

	1	2	3	4	5	6	7	8	9	10
1	1.00									
2	0.81	1.00								
3	0.78	0.77	1.00							
4	0.73	0.73	0.71	1.00						
5	0.71	0.73	0.69	0.65	1.00					
6	0.65	0.66	0.63	0.59	0.57	1.00				
7	0.55	0.56	0.53	0.50	0.51	0.46	1.00			
8	0.51	0.51	0.48	0.46	0.46	0.42	0.37	1.00		
9	0.50	0.51	0.48	0.46	0.46	0.42	0.36	0.32	1.00	
10	0.47	0.46	0.44	0.42	0.41	0.37	0.32	0.30	0.28	1.00

where the indexes correspond to following energy ranges:

1 = 0.1 - 0.5 MeV
2 = 0.5 - 1.0 ...
3 = 1.0 - 2.2 ...
4 = 2.2 - 4.0 ...
5 = 4.0 - 5.5 ...
6 = 5.5 - 7.0 ...
7 = 7.0 - 8.5 ...
8 = 8.5 - 11.0 ...
9 = 11.0 - 14.0 ...
10 = 14.0 - 20.0 MeV

were smoothed by chi-square fitting the evaluated data set with a conventional spherical optical model. Ten parameters were varied in the fitting procedure: real and imaginary radii, diffusenesses, and strengths (with the latter given a quadratic energy dependence). The fitting was carried out in three energy segments and the results smoothly blended together. The resulting optical-model parameters are rational but should not be construed as more than a parameterization of the evaluated data set for the purposes of smoothing. The model-calculated results agree with the experimentally based evaluated cross sections to well within the latter's uncertainties, excepting only a very few of the lower-energy values which are sensitive to fluctuations. Thus, the model-smoothed results were taken as representative of the final energy-averaged evaluation.

Below ≈ 5.0 MeV, the resonance fluctuations become increasingly prominent as the energy decreases. These fluctuations were introduced into the evaluation by selecting the high-resolution experimental results of Ref. 8 over relatively narrow energy ranges and renormalizing them so that their average value was consistent with that of the energy-averaged evaluation. The normalization factors were generally very small (on the order of a percent). The final result is an evaluation that has the energy-averaged magnitudes outlined above, and the detailed resonance fluctuations of the best-resolution experimental results. There is a limitation in ENDF formats as to the number of energy points. Taken in all its detail, the fine-resolution results of Ref. 8 considerably exceed that limit. Thus, unavoidably, some of the definition of the fine resolution data of Ref. 8 had to be compromised. This will not affect the use of the present file in the vast majority of applications. However, a user interested in the ultimate detail of the resonance data should refer directly to the best contemporary resonance data (e.g., that of Ref. 8).

The present evaluated neutron total cross sections are illustrated in Fig. 3, together with the comparable values from ENDF/B-V. Clearly, there are some very large differences between the two evaluations (particularly in the range 2.5 to 5.0 MeV where differences can be 10%-15%), and these differences will have a significant impact on other aspects of the evaluation.

The experimental data base for evaluation is now relatively good up to ≈ 16.0 MeV. At higher energies there are only two comprehensive experimental data sets, and they are not in particularly good agreement. Additional experimental information is desirable above ≈ 16.0 MeV.

III. ELASTIC SCATTERING

The experimental data base for the evaluation of neutron elastic scattering relies very heavily on the extensive new work of Ref. 2, undertaken in the support of this evaluation. Additional experimental information was obtained from Refs. 35 to 40. This experimental data base gives very good coverage of the elastic-neutron-scattering process from a few-hundred keV to 10.0 MeV. It is discussed in detail in Ref. 2, and those interested in more depth are directed thereto.

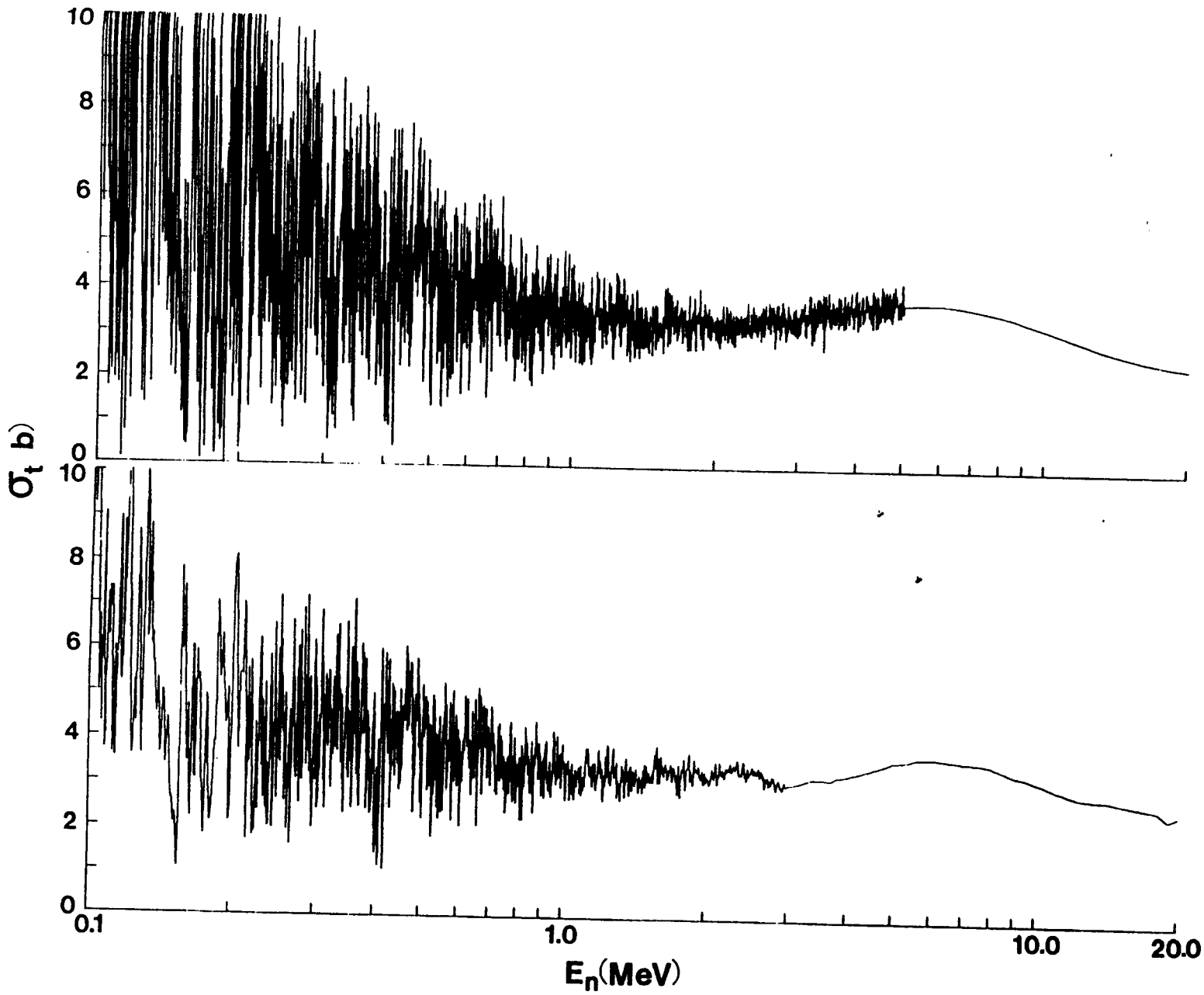

Fig. 3. Comparison of the present evaluated total cross sections (upper) with those of ENDF/B-V (lower).

Reference 2 gives detailed attention to the fundamental and applied aspects of an optical-statistical model. These considerations deal with the effects of deformation attributed to the coupling of an $f_{7/2}$ proton to the yrast 2^+ level in ^{60}Ni, the coupling of real and imaginary potentials via the dispersion relationship, the energy dependencies of potential geometries and strengths, and the effect on the potential of the Fermi surface. The resulting model is very successful in describing the observed elastic scattering, provides a very good description of the total cross section to 20.0 MeV, and the observed inelastic-scattering cross sections. This model and comparisons with experimental observations are discussed in detail in Ref. 2.

The evaluation uses the above model to determine the elastic-scattering cross section from the onset of continuum inelastic-scattering processes at ≈ 3.0 MeV to 20.0 MeV. The calculated values were very slightly (≈ 1%) adjusted so that the concurrently calculated total cross sections agreed with the above evaluated total cross sections. Below ≈ 3.0 MeV, the evaluated elastic-scattering cross section was determined from the difference between the total cross section and the other partial cross sections. This procedure assures the requisite internal consistency of the file, although it results in essentially all of the fluctuating structure in the total cross section appearing in the elastic channel. Of course, this is only an approximation, but there is little alternative given the requirement of internal file consistency and the fact that elastic-scattering cross sections are not measured with resolutions anywhere near comparable with those used in the total cross-section measurements.

The uncertainties associated with the above elastic-scattering evaluation are difficult to quantify. However, some guidelines are:

0.1 - 1.0 MeV	≈ 1.0%
1.0 - 10.0 MeV	≈ 3.0%
10.0 - 20.0 MeV	≈ 3.0 to 5.0%

These are relatively small uncertainties and, combined with the above total cross sections, imply reasonably good knowledge of the nonelastic cross section in regions where it is of appreciable magnitude.

The above model, known to give a good description of the observed angular distributions,[2] was used to calculate the evaluated angular distributions with the results illustrated in Fig. 4. In the file these distributions are expressed as Legendre polynomial coefficients. All of the distributions are consistent with Wick's Limit.[41]

The present evaluated elastic-scattering cross sections are significantly different from those given in ENDF/B-V, as illustrated in Fig. 5. They result in nonelastic cross sections that also significantly differ from those implied by ENDF/B-V, though the effect of the above-cited differences in evaluated total cross sections are the dominant factor in the differences between the nonelastic cross sections implied by the two evaluations. Clearly, these relatively large differences in nonelastic cross

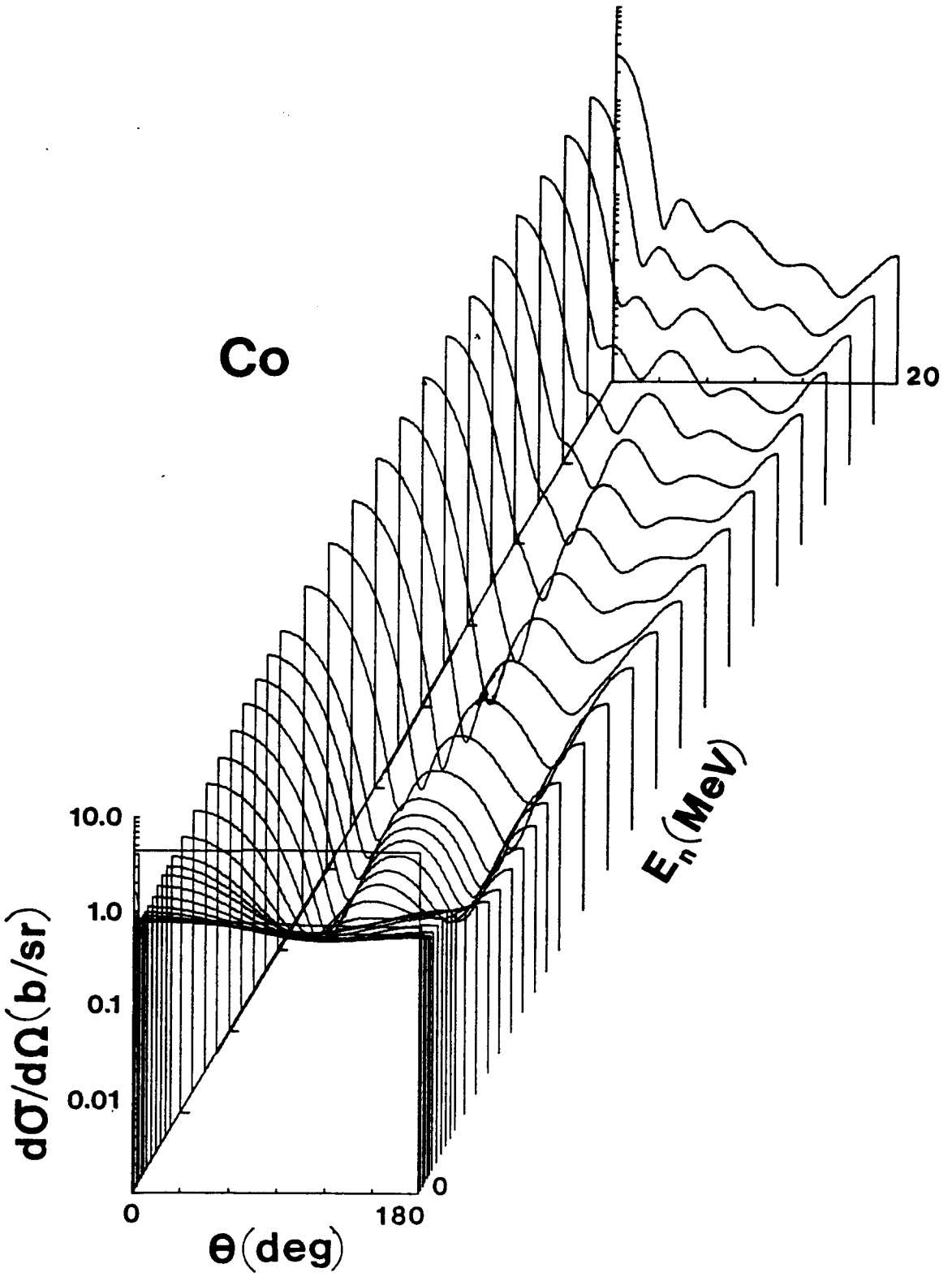

Fig. 4. Evaluated differential elastic-scattering cross sections of cobalt.

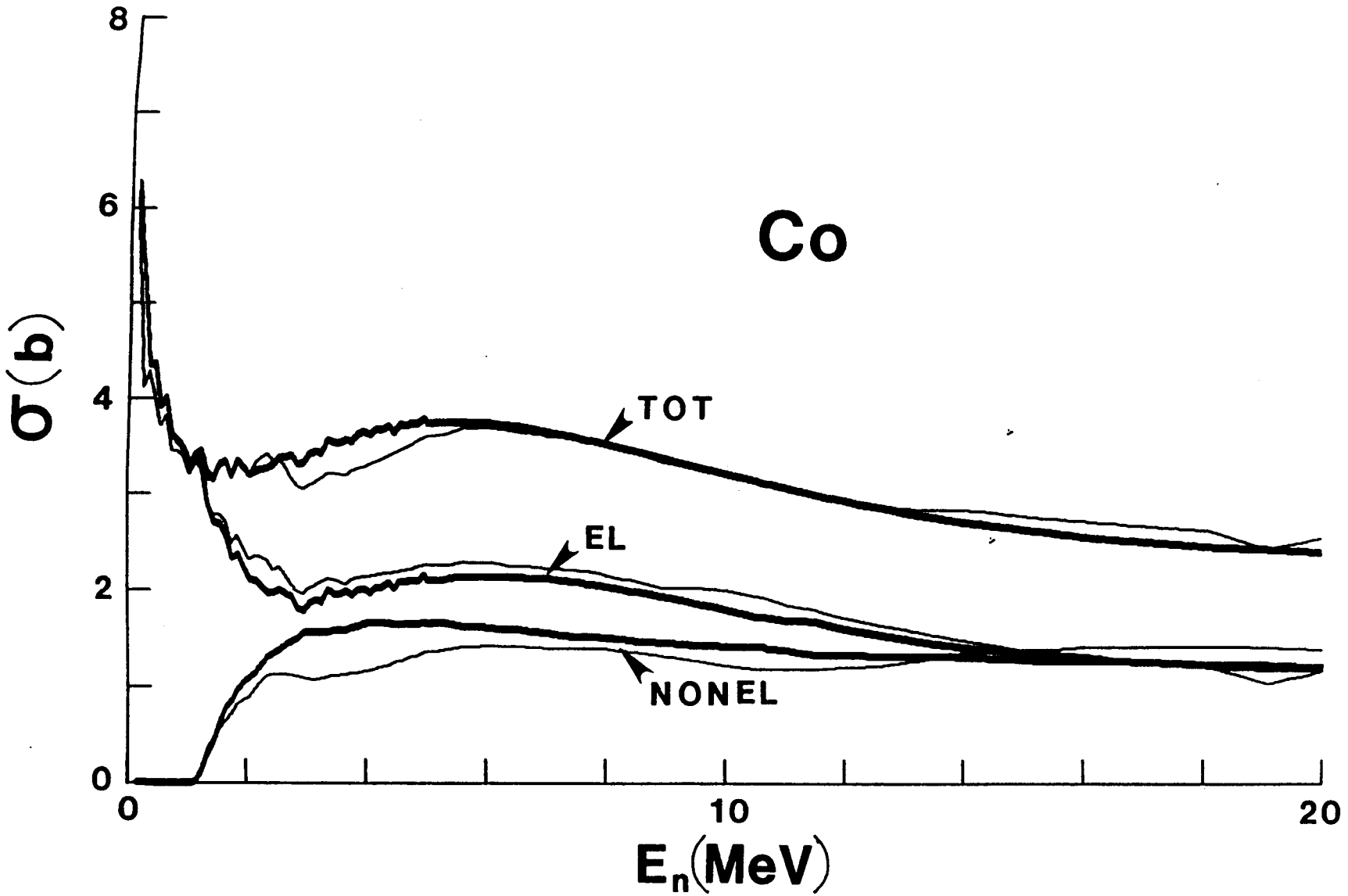

Fig. 5. Comparison of the present evaluated (heavy curves) total, elastic and nonelastic cross sections with those given in ENDF/B-V (light curves). The comparisons are on a 100-keV energy-averaged basis.

sections will be reflected in considerable differences elsewhere in the evaluation.

The present evaluation is soundly founded on observations below ≈ 10.0 MeV. It is believed that it is quite reliable above ≈ 10.0 MeV, but at these higher energies it is based entirely upon a calculational extrapolation through a region where the potential is changing its character.[2] One could have more confidence in the evaluation if there were several good measured elastic-scattering distributions available between 10.0 and 20.0 MeV, perhaps at ≈ 2.0 MeV incident-energy intervals.

IV. INELASTIC SCATTERING

A. Discrete Processes

The present evaluation uses the nineteen excitation energies of Table 3, taken from Ref. 42, and the calculated inelastic-excitation cross sections of Ref. 2, to provide the relative energy-dependent cross sections for the excitation of the respective levels. The requisite nuclear model, described in detail in Ref. 2, includes the direct excitation of five of the first seven levels assuming a weak-coupling model. The calculated inelastic-scattering cross sections were renormalized by small amounts (e.g., generally by several percent) to bring them into subjectively judged improved agreement with observations. The calculated energy-dependent cross-section shapes were retained throughout the evaluation. Illustrative evaluated results are compared with measured values in Fig. 6. In a number of instances, the observations refer to the combined contributions of two or more levels, and thus the relevant evaluated components were summed for comparisons with the experimental results. The appreciable high-energy components of the five low-lying levels due to the above-cited direct excitations are clearly evident, particularly when comparing measured and evaluated quantities for the combined excitation of all levels below ≈ 1750 keV, at incident energies above ≈ 5.0 MeV.

The uncertainties associated with the above cross sections are difficult to assess, as the experimental values scatter and the model, while complex, is a simplification of the physical reality. Generally, experimental results obtained in direct (n,n') measurements were relatively consistent, while those deduced from (n;n',γ) measurements frequently are very discrepant, probably due to uncertainties in the interpretation of the decay schemes. Uncertainty guidelines are: 5-10% on the sum of the discrete excitations, approximately the same for the prominent levels or sums thereof, and larger for the weakly excited and isolated levels. The uncertainties are in the context of an energy average only.

The angular distributions of the majority of the emitted-neutron groups were taken to be isotropic. This is a reasonable assumption as the compound-nucleus reaction is the dominant process, and it leads to emitted-neutron symmetry about 90° and distributions that are nearly isotropic.[2] Neutrons

Table 3. Excited levels used in the evaluation.[a]

N°.	E_x(MeV)	J^π
1	1.0999	$3/2^-$
2	1.1903	$9/2^-$
3	1.2919	$3/2^-$
4	1.4340	$1/2^-$
5	1.4589	$11/2^-$
6	1.4815	$5/2^-$
7	1.7445	$7/2^-$
8	2.0613	$7/2^-$
9	2.0879	$5/2^-$
10	2.1528	$7/2^-$
11	2.1824	$7/2^-$
12	2.2053	$5/2^-$
13	2.3950	$9/2^-$
14	2.4783	$5/2^-$
15	2.5402	$5/2^-$
16	2.5842	$9/2^-$
17	2.7128	$1/2^+$
18	2.7807	$5/2^-$
19	2.8252	$7/2^-$

[a] Properties taken from ref. 42.

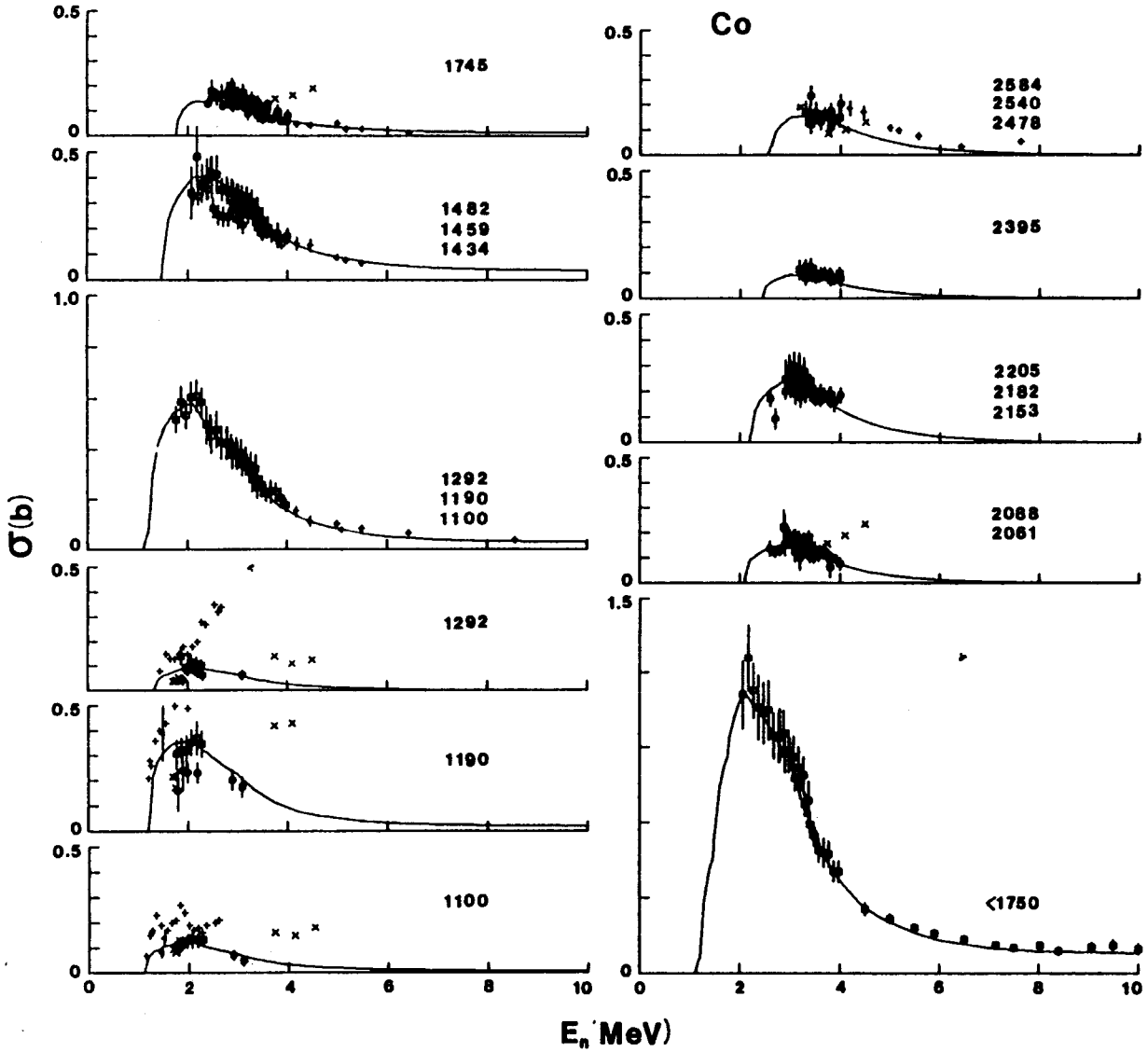

Fig. 6. Illustrative comparisons of measured (symbols) and evaluated (curves) inelastic-scattering cross sections of ^{59}Co. The contributing excitation energies (in keV) are given numerically in each portion of the figure. The experimental symbols are referenced as follows: □ = Ref. 2, O = Ref. 47, + = Ref. 48, X = Ref. 49, ◇ = Ref. 37, ← = Ref. 38, and ⋉ = Ref. 50.

resulting from the excitation of the five levels attributed to the coupling of the $f_{7/2}$ proton to the yrast 2^+ level in ^{60}Ni are emitted very anisotropically at higher energies.[2] In these five cases the evaluation uses the calculated angular distributions of Ref. 2, which have been shown to give a good description of the collective excitation of these five levels. There may be some detailed differences between the distributions resulting from the excitation of these individual levels, but at the higher energies, where the anisotropy is prominent, the user will generally lump the contributions from the five levels into a single group. Thus, the evaluation uses the same anisotropy for each of the five levels.

The present evaluation is compared with that of ENDF/B-V in Fig. 7. The present work contains nearly twice the number of excitations, and they extend to higher energies. Generally, the present evaluation results in 10-20% more aggregate inelastic cross section than that of ENDF/B-V and has a different shape above ≈ 3.0 MeV where competition from the continuum of higher-energy levels is a factor. ENDF/B-V contains no direct-reaction components; thus, it does not display the significant high-energy cross sections of the present evaluation.

Significant improvements in the present evaluation will require more detailed measurements and models, particularly at higher energies. Neither is trivial. The experimental aspects of such problems will require very good resolution, especially at lower energies where fluctuations are large.

B. Continuum Processes

Continuum inelastic-neutron-scattering cross sections start at 3.0 MeV, the upper energy limit of detailed knowledge of discrete-excited states in ^{59}Co. Their magnitudes were determined from the difference between the nonelastic cross sections, implied by the above neutron total and elastic-scattering cross sections, and the sum of the other partial cross sections. This procedure assures file consistency. There were small adjustments in the magnitudes to smooth the emission spectra described below. These adjustments were in the regions of rapidly changing cross sections, for example, where the (n,2n) cross section rises rapidly from threshold.

The continuum neutron-emission spectra are made up of contributions from the (n,n'), (n;2n), (n;n',p + n;p,n'), (n;n',α + n;α,n'), and smaller (n;n',X) processes. The individual components can be observed only over limited energy ranges, if at all. More generally, the observation is of the totality of the emission spectra. The primary form of this evaluation assumes isotropic neutron emission and presents the spectral energy distributions in File-5. A secondary version of the evaluation will include File-6 angle-energy correlations and will be documented elsewhere.

The individual spectra were calculated using the computer codes ALICE[43] and CADE.[44] ALICE calculates cross sections and emission spectra using the hybrid model for pre-compound processes and the Weisskopf-Ewing evaporation model for compound decay.[45] CADE carries out compound-nucleus calculations

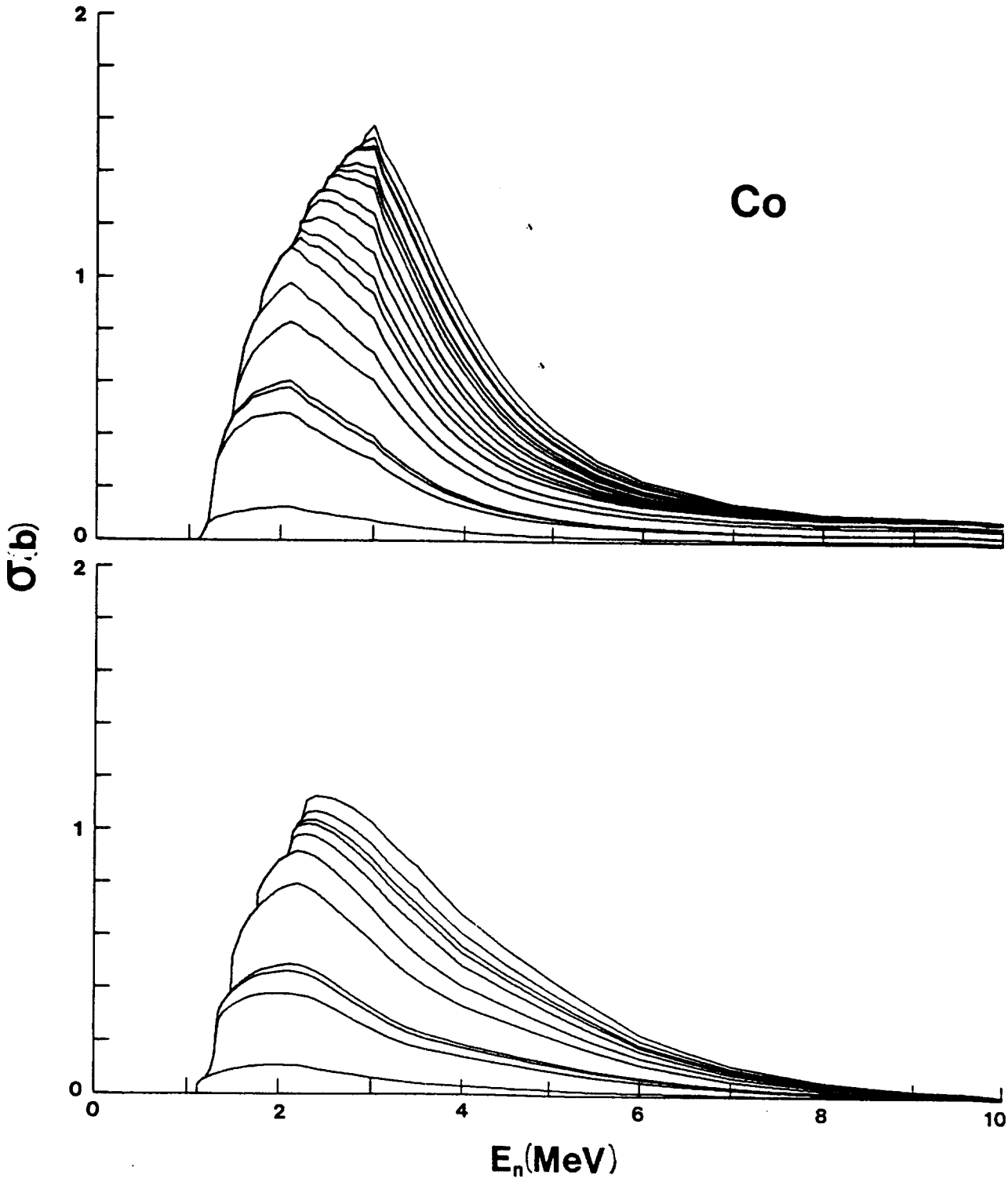

Fig. 7. Cumulative evaluated inelastic-excitation cross sections of ^{59}Co. Curves indicate the sum of the cross sections as contributions from various levels are introduced. The upper portion of the figure is taken from the present work, the lower from ENDF/B-V.

using the Weisskopf-Ewing method and the level-density formalism and parameters of Brancazio and Cameron.[46] Gamma-ray emission is described by the giant-dipole resonance formalism. For simplicity, it was assumed that the pre-compound process only involves the emission of a single nucleon. This is a reasonable assumption up to 20.0 MeV, at which energy multi-particle pre-compound emission has risen to only a few percent of the total reaction cross section. The calculated cross sections for all reactions that involve the emission of three or more particles were very small and consequently were ignored.

The evaluation uses ALICE to calculate the spectra and CADE to divide the components among the various 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 incident energy of the neutron, E is the relative energy of the emitted neutron, $D_{n_1}(E_{in},E)$ is the energy distribution of the relative motion of the neutron when it is the first particle emitted, and $P_{n_1,\gamma}(E_{in} - E)$ is the probability that the residual nucleus decays by γ-ray emission when its excitation energy is $(E_{in} - E)$ (leading to the (n,n') reaction). Since it is assumed that no reaction involving three emmited particles is possible, the expression for the (n,2n') meutron 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 to calculate the P_n terms.

The difference between the calculated total reaction cross section and that obtained from the above evaluation is generally less than 10%. The difference could probably be removed by adjustment of optical-model and other parameters used in the calculation, but such adjustments were not undertaken, as the effect on the 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 processes outlined in the other sections of this document.

The calculated spectra were transformed to the laboratory system, maintaining energy correlation but assuming no angle correlation. When the various spectral components were combined, neutron emission spectra were

obtained which were qualitatively consistent with those observed experimentally.[39] The calculated emission spectra have some small artifacts due to non-exact meshing of the various components in regions of rapidly varying cross sections. These artifacts are of no applied significance. However, consideration of the shape of the emission spectra did offer guidance as to the evaluated cross sections in regions where there is no experimental information. This is particularly true of the (n;n',p) and (n;n',α), generally, and of the (n,2n') and (n,n') cross sections in some energy regions.

The various continuum emission spectra outlined above are somewhat different from those given in ENDF/B-V. It is not clear that the differences are significant, as both evaluations must rely very largely on calculational or systematic estimates and, as a consequence, may have large uncertainties. The latter will not be appreciably resolved until much more detailed experimental information on the neutron emission spectra is available at a number of incident-neutron energies. Some such measurements are in progress, but they are slow and difficult. Even with far more definitive experimental knowledge of neutron emission spectra, it will remain necessary to use theoretical calculations to break the observed spectral values into the components necessary for the evaluation. Thus, it is desirable that there be a carefully correlated measurement and calculation effort in this continuum neutron-emission area.

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

A review of the index CINDA[7] and the experimental data file[1] indicates a wealth of differential information for the (n,2n) reaction. The available experimental data[51-83,139] were compiled and the available documentation reviewed in order to determine the adjustments required to account for recent changes in decay constants, neutron-fluence standards, etc. A careful assessment was made of the errors in these data sets. In several instances, the errors were enhanced because certain important details of the measurements that have a bearing on error assessment were missing in the documentation. Attention was paid to error correlations within each multi-point data set. However, correlations between distinct data sets could not be readily traced and therefore were neglected in the evaluation. Although this procedure is clearly not entirely correct, it avoids many difficulties in the analysis of the data for the evaluation, and seems justified in view of the anticipated small improvement in the evaluation resulting from the complex treatment of inter-set correlations.

The experimental data available for the present evaluation are shown in Fig. 8, after applying the above-mentioned adjustments, along with the ENDF/B-V evaluation, and the specific 14-MeV evaluation recently carried out at this laboratory by Evain et al.[84] This figure illustrates several points. ENDF/B-V is generally larger than both the main body of the experimental data, and the evaluated 14-MeV result of Evain et al. (ENDF/B-V is based largely on nuclear-model calculations.) It is also evident that there is considerable scatter in the experimental data, even as corrected, and this

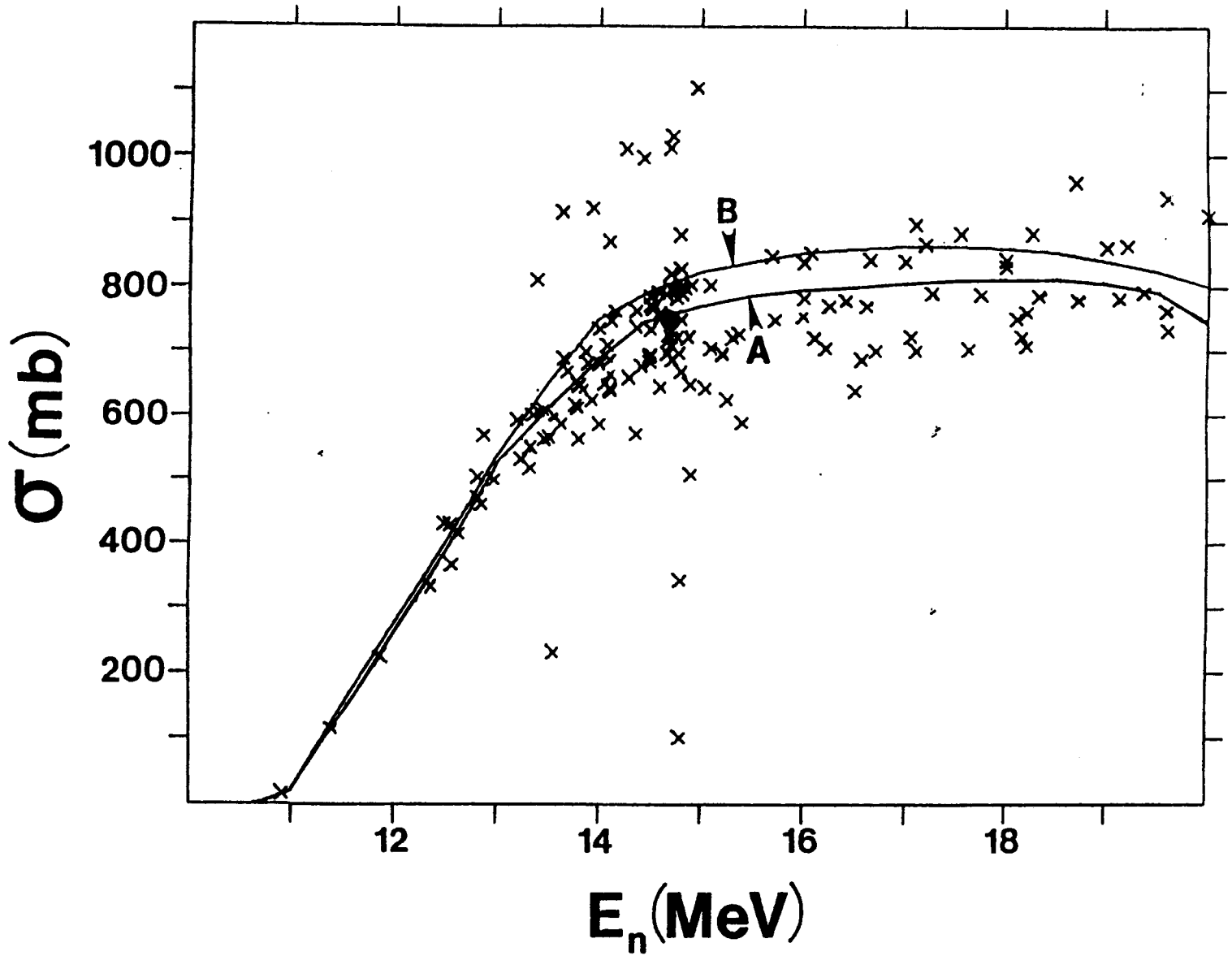

Fig. 8. Experimental data (X) and evaluated cross sections for the ^{59}Co(n,2n) reaction. Corrections have been applied to the data as described in the text. For clarity, author and error notation have been omitted from the data values. Evaluations are indicated by: A = the present evaluation, B = ENDF/B-V, and (●) = the 14.MeV evaluation of Evain et al.[84]

presents difficulties in the present evaluation, as it did for the evaluation of Evain et al.

The present (n,2n) evaluation is largely based upon experimental data, most of which are activation results. The reaction is very amenable to investigation by the activation method. The reaction product, ^{58}Co, decays with a half life of 70.916 days,[85] and the decay occurs by positron emission (15%) and electron capture (85%), with an 0.811-MeV γ-ray emitted in 99.44% of all decays.[86] Consideration was given to ENDF/B-V in order to guide the present evaluation in regions where experimental data were relatively sparse (i.e., below 12 MeV and above 18 MeV). The least-squares evaluation code GMA[2] was used in the present work. ENDF/B-V was accepted as a-priori information in two contexts: It provided a shape used to shift the experimental data to the selected grid-point energies required by GMA. Furthermore, in renormalized form (see below), it supplemented the available data in regions where measured values were sparse or nonexistent in order to stabilize the least-squares GMA procedures. The magnitude of ENDF/B-V was not deemed adequate for the above supplemental usage owing to the fact that it lies above the general trend of the experimental data. Consequently, ENDF/B-V was reduced everywhere by 7%. This reduction factor was chosen so that the adjusted ENDF/B-V yielded reasonable shape and normalization agreement with the consistent data sets available from Paulsen and Liskien[59] and Frehaut et al.[60] Taken together, these two sets of data span most of the energy range of the present evaluation. Values were then obtained from this adjusted curve at the grid energies, and these were introduced, weighted in accordance with the File-33 covariance information of ENDF/B-V, as artificial data points. By this method, the ENDF/B-V evaluation was effectively introduced into the present evaluation procedure as an a-priori result in the Bayesian sense. The impact of ENDF/B-V on the present evaluation is most pronounced in energy regions where the data are sparse. Where the available data are extensive, the present evaluated results are almost entirely dominated by these data rather than by ENDF/B-V. In this sense, the present evaluation, overall, is rather weakly influenced by earlier evaluations.

Before running GMA, some of the data points that appeared to be the most discrepant with respect to the complete body of data were rejected. The resulting evaluation was found to be quite reasonable, based upon comparisons with the underlying data. However, non-physical fluctuations were in evidence, particularly at energies below 15.0 MeV. This is a common occurrence in computer-evaluation procedures that are based on experimental data sets within which there exist obvious discrepancies. One method of dealing with this situation is to smooth the results using procedures such as spline fitting. That approach was not employed in the present work. Instead, a few additional data points were selectively rejected on a second pass of GMA in order to eliminate most of the fluctuations for cosmetic purposes. Since the changes in the evaluated results as a consequence of this procedure were smaller than the predicted uncertainties of the evaluation, this approach seems justified. The errors in the evaluated results produced by this procedure were, in fact, relatively small, particularly in the vicinity of 14.0 MeV where the number of data points averaged within the selected grid intervals was rather large (e.g., as many as 25 in the 0.5 MeV interval about 14.5 MeV). These errors appeared

subjectively to be too small in view of the many inconsistencies observed in the data base accepted for the evaluation. Unfortunately, the version of GMA used in the present evaluation does not give a chi-square value which could be used to judge the degree to which the errors generated by the evaluation process ought to be enhanced (e.g., as described by Evain et al.[84]) For guidance on how to deal with this problem, we turned explicitly to the work of Evain et al. In this earlier work, the cross section at 14.7 MeV was evaluated employing essentially the same data base that was considered in the present evaluation. The result is about 1.5% smaller than that obtained in the present evaluation, with an enhanced error (based upon an examination of chi-square) of 2.4%. The error obtained in the present work using GMA was < 1% for this energy region. The addition of new high-quality data available since 1984 suggests that the uncertainty in the vicinity of 14.0 MeV ought to be reduced below the 2.4% value obtained by Evain et al. A value of ≈ 2% was selected rather arbitrarily as a compromise between the very small errors from GMA and the larger error of Evain et al. This consideration indicates that all the errors obtained in the present work using GMA ought to be enhanced by about a factor of two, while at the same time preserving the correlation pattern from the analysis. An equivalent procedure would have been to arbitrarily double the input errors (both random and systematic) so as to preserve the correlations. This enhancement of errors can be viewed as a penalty imposed by the existence of significant discrepancies in the data base, relative to the quoted errors of the data.

The present evaluated results fall noticeably below ENDF/B-V (e.g., by ≈ 8% around 16 MeV) over the entire energy range. The uncertainties range from as much as ≈ 60% very near threshold to as little as 2% in the vicinity of 14 MeV. The results of this evaluation agree very well with that of Evain et al.[84] The present evaluation is compared with the experimental data, with ENDF/B-V and with the evaluation of Evain et al. in Fig. 8. Reasonably good agreement is observed between the present evaluation and most of the recent high-quality results from the literature (e.g., Refs. 68-70,139).

The threshold of the (n,3n) reaction is 19.353 MeV. There have been no experimental results reported below ≈ 21.0 MeV, and at that energy the cross section is very small, 21 ± 11 mb.[52] In view of the very high threshold energy and the small cross sections, even at E > 20.0 MeV, the (n,3n) process was not considered in the present evaluation.

The present evaluation assumes (n,2n) neutron emission only through compound-nucleus channels, and the emission is isotropic. The relative neutron-emission spectra were obtained as a part of the general consideration of neutron-emission spectra outlined above in Sec. IV, above.

VI. RADIATIVE CAPTURE

Neutron capture in ^{59}Co results in either the 10.5-minute activity of the 59-keV (2+) isomeric state or the 5.3 year activity of the ground state (5+).[86] In principle, the latter activity determines the neutron-capture cross section, but the relatively long half-life and the small cross sections

make activity measurements tedious, and they appear to never have been carried out. Isomer cross sections have been experimentally determined, but their conversion to total capture cross sections requires an energy-dependent knowledge of the isomer ratio which is uncertain. Direct γ-ray-detection methods do give a knowledge of the total capture cross section.

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]. The resulting data base, given in Refs. 67, 87-102 and shown in Fig. 9 (above 100 keV), is sparse. Most of it is relevant to low or thermal energies covered by the above resonance representation. The work of Refs. 87 and 92 employed direct gamma-ray-detection methods and spans a significant energy range. In addition, there are the results of the direct-detection measurements of Refs. 93 and 101 near 14.0 MeV. These results are relatively consistent with isomer results of Ref. 102 in the sense that the energy-dependent shapes are somewhat similar and that the isomer values are a reasonable fraction of the total. However, there appear to be discrepancies in the structure between isomer- and total-capture results. This is perhaps not surprising, considering the fluctuating cross sections and various experimental resolutions involved. More of a concern is the general energy-dependent trend of the total-capture results which is not what one would expect from simple theoretical estimates.

Given the above very much less than definitive experimental situation, the present evaluation relies upon a statistical-model calculation using the dipole model of the code ABAREX,[103] the optical potential of Ref. 2, and the adjustment of the $\ell = 0$ strength function to achieve a subjectively judged "good" description of the available experimental data. In addition, a small direct-capture component was added at high energies. From the point of view of neutronic calculations, that addition is essentially a cosmetic effect, as the direct-capture cross sections do not exceed 1 mb. The resulting evaluation is illustrated in Fig. 9. Of course, it does not portray the scatter of the lower-energy experimental values but it does, on the average, properly account for channel competition and for the direct-capture component that was added at high energies. The uncertainty in the evaluation is relatively large, perhaps 10-20% below a few MeV and even larger at higher energies. Salvation lies in the relatively small magnitude of the cross section over most of the energy range (a few mb or less).

Figure 9 shows the comparable cross section from ENDF/B-V. Below 1.0 MeV it appears to be an empirical construction through the only available set of data. On the average, its magnitude is relatively consistent with that of the present evaluation, but there are large local variations and an unusual low-energy behavior. Above approximately 1.0 MeV, the ENDF/B-V values are considerably larger than those of the present work and larger than any experimental result, and there is a peculiar discontinuity at higher energies. With the available experimental information, a clear choice between the two evaluations is not possible below 1.0 MeV. At higher energies, the present work seems more appropriate and is supported by the theoretical concepts underlying the model calculation.

The present, or any similar, evaluation cannot be significantly improved without a considerable improvement in the experimental data base.

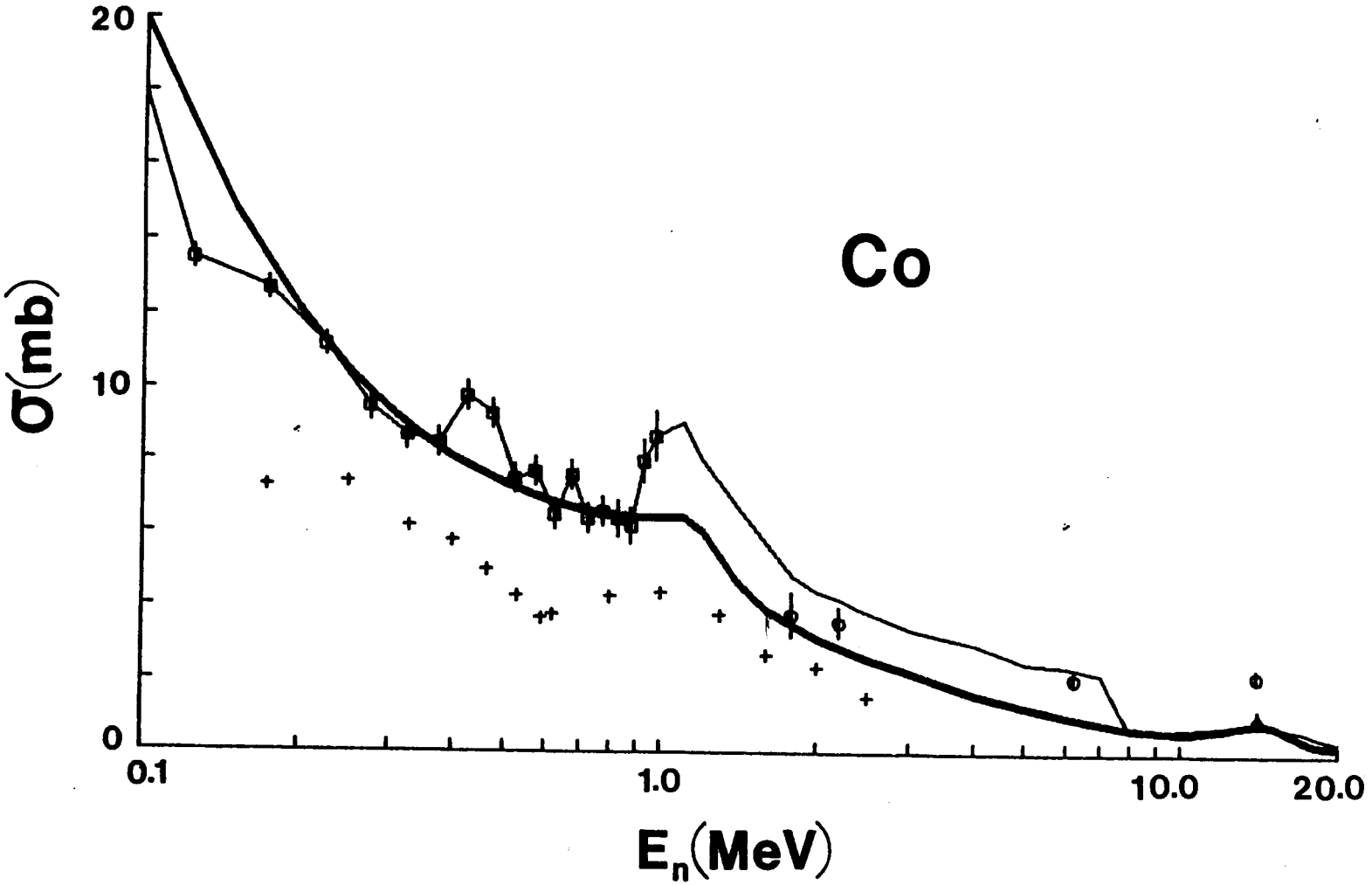

Fig. 9. Comparison of measured and evaluated (n,γ) cross sections of ^{59}Co. Measured values are indicated by data symbols with isomer results indicated by "+". The present evaluation is shown with the heavy curve, and that of ENDF/B-V with the light curve.

Measurements using activation techniques will be tedious due to the small cross sections and the long half-life of the ground state, but otherwise are not particularly difficult. Broad experimental resolutions should be used with attention to possible thermal-neutron contamination of the results. Concurrently, it would be useful to have several additional comprehensive sets of data obtained with different prompt-detection techniques.

VII. (n,α) PROCESS

The ^{55}Co(n,α) reaction produces ^{56}Mn, which decays with a $t_{1/2}$ = 2.578 hours.[96] The Q-value for the reaction is + 0.327 MeV.[95] However, due to coulomb-barrier effects, the cross section is negligible for all practical purposes below ≈ 4.0 MeV. There exists an extensive data base for this reaction,[7] most of it derived from activation measurements of ^{56}Mn. The ENDF/B-V value for this reaction is based upon a 1970 evaluation by Bresesti et al.,[104] and it needed revision in order to take into consideration the extensive new information which has accumulated over the intervening years. The ENDF/B-V evaluation is compared with the available data in Figs. 10 and 11. Figure 11, a semilog plot, clearly shows the limitation of the evaluation in the threshold region, which is of particular importance in dosimetry applications.

The details of the present evaluation of this reaction have been reported elsewhere,[105] and only a brief summary will be provided here. The method of generalized least squares[106] was employed over the energy range 5.5 to 18.0 MeV. The ENDF/B-V evaluation was used as the a-priori data set in an adjustment procedure, which incorporated the following new information: i) a set of differential cross sections obtained at this laboratory[105] covering the energy range 5.0 to 10.0 MeV, ii) a detailed evaluation of data available over the energy range 13.0 to 15.0 MeV up to 1985,[84] and iii) the results of recent 14-MeV measurements at this laboratory.[107] In the threshold region, model calculations were performed to yield the cross-section shape into the micro-barn range below ≈ 4.0 MeV. The present calculation eliminates the structure in the cross section shown in ENDF/B-V, since it did not appear justified from the available data.

The results of the present evaluation are shown in Figs. 12 and 13. The major changes from ENDF/B-V correspond to the energy range from threshold to 5.5 MeV and from 13.0 to 16.0 MeV. It is found that the present evaluation is in better agreement with the recent precise fission-spectrum neutron integral data[108,109] than is ENDF/B-V. Furthermore, the predicted uncertainties associated with the present evaluation are generally 5% or less over most of the fission-spectrum response range, indicating that the evaluation meets the stated accuracy needs for dosimetry applications in fission- and fusion-energy systems.[110]

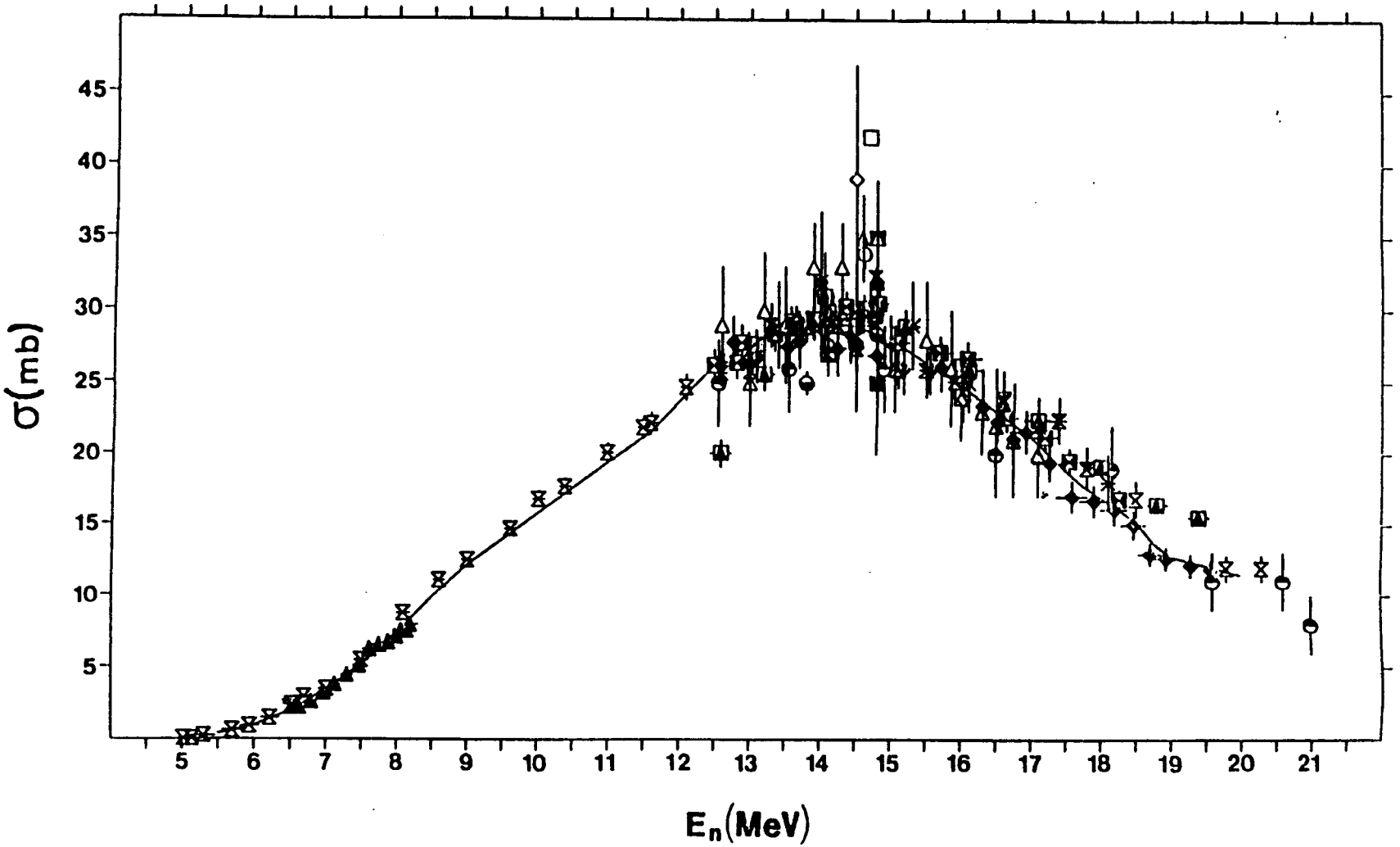

Fig. 10. Comparison of ENDF/B-V (n,α) cross section (curve) with the available data base from threshold to 20.0 MeV (symbols).

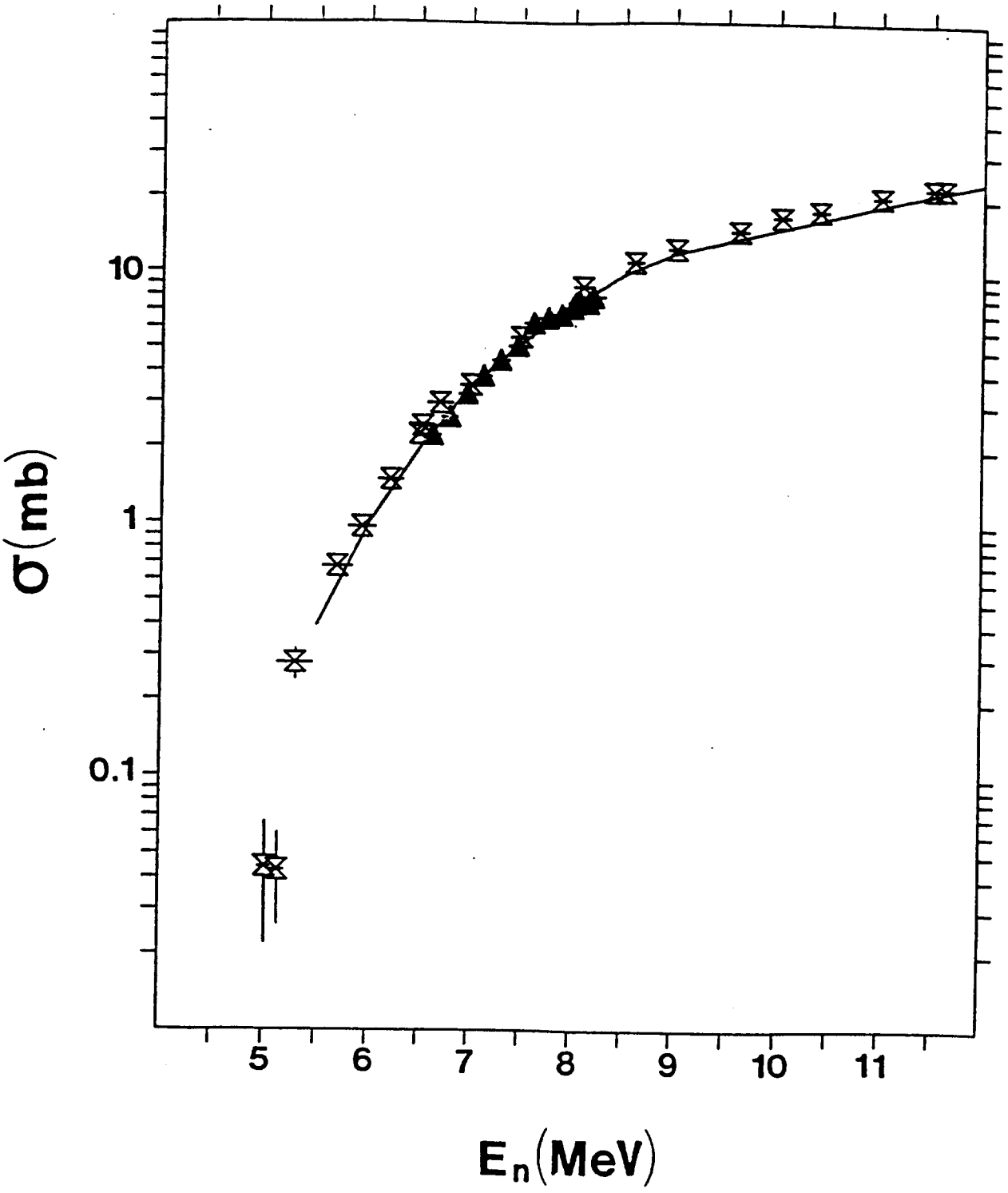

Fig. 11. Comparison of ENDF/B-V (n,α) cross section (curve) with the available data base from threshold to 12.0 MeV (symbols).

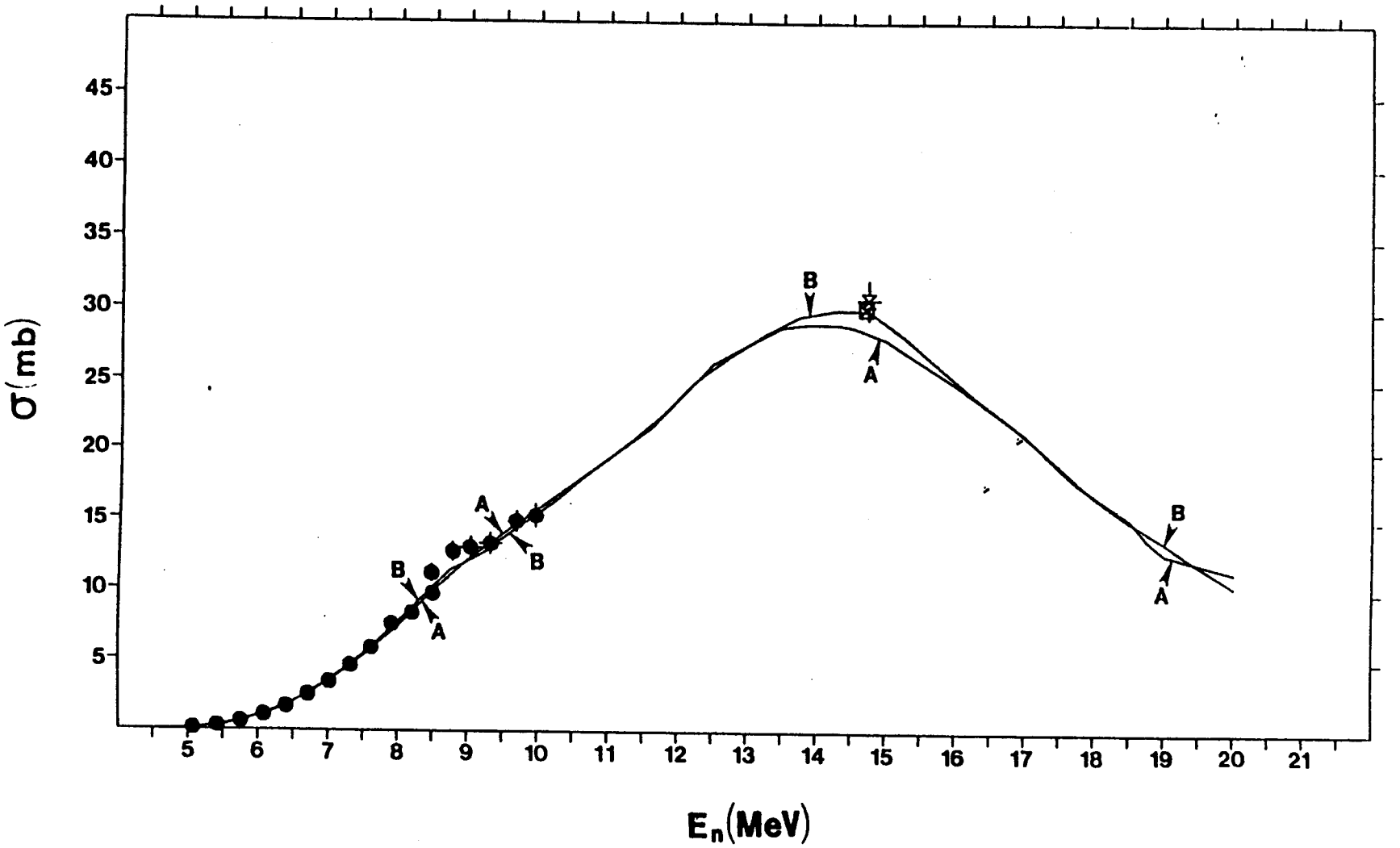

Fig. 12. Comparison of ENDF/B-V (n,α) cross section (A) and the present evaluation (B) with the new information (e.g., Ref. 105) (symbols) used in the evaluation process from threhold to 20.0 MeV.

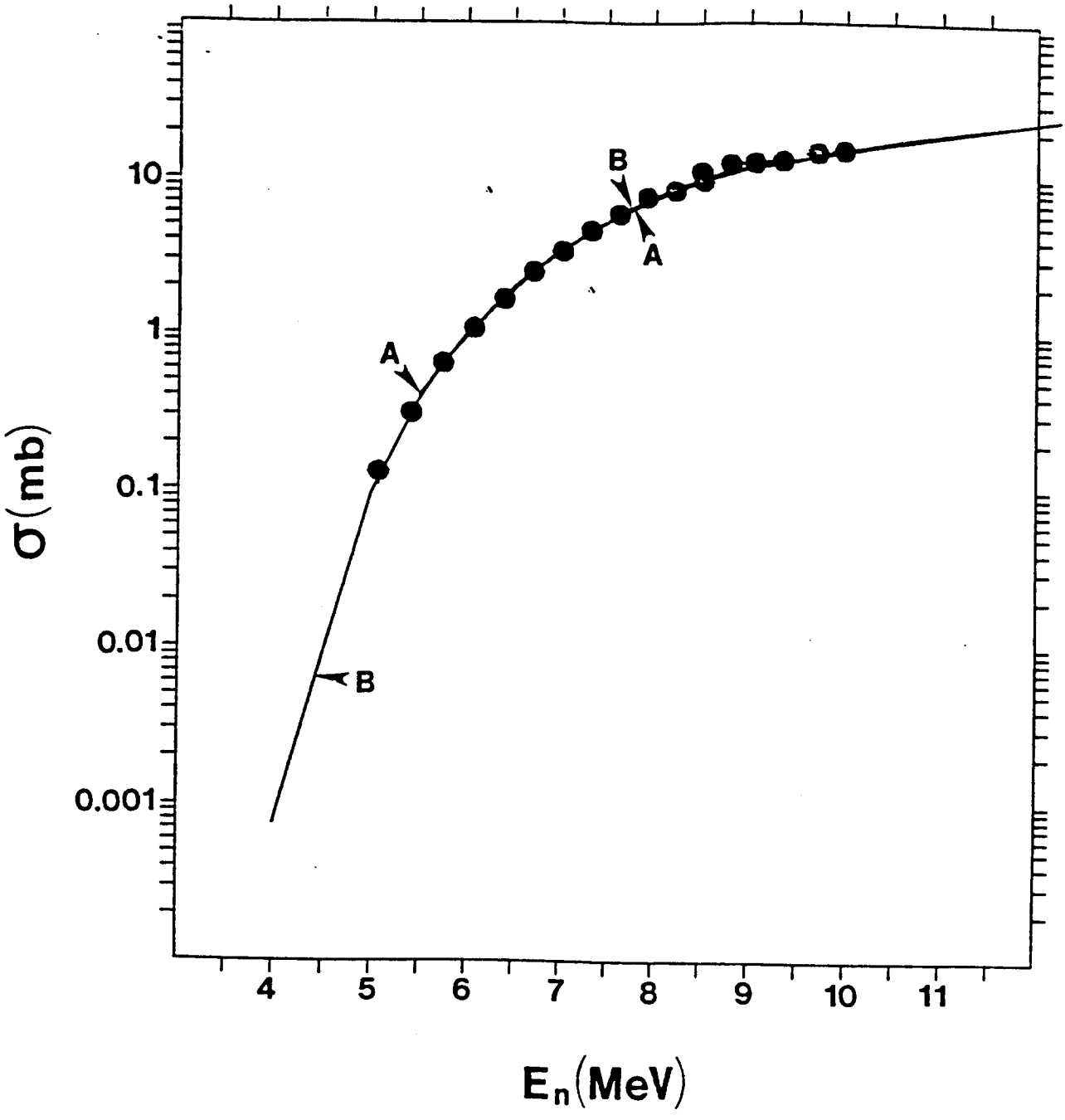

Fig. 13. Comparison of ENDF/B-V (n,α) cross section (A) and present evaluation (B) with the new information (symbols) used in the evaluation from threshold to 12.0 MeV.

VIII. (n,p) PROCESS

A review of the nuclear-data index CINDA[7] and the experimental data file[1] indicates that considerable differential information exists upon which to base an evaluation of the (n,p) reaction. The available experimental data (Refs. 56, 62, 64, 77, 79, 82, 111-122) were compiled and the corresponding documentation reviewed in order to determine appropriate adjustments of the data due to recent changes in standards, decay constants, etc.[85,86] An assessment of errors was made, as described above, in the context of the (n,2n) process, and, as in that case, correlations within sets were considered but were ignored between data sets. Again, data uncertainties were enhanced in those cases where the documentation left doubt as to their reliability.

The experimental data available for the evaluation are plotted in Fig. 14 in their corrected form, together with the ENDF/B-V evaluation and the 14-MeV evaluation of Evain et al.[84] It became evident early on that the present evaluation could not be based entirely upon the experimental data. In particular, in the 10 - 13 MeV region, where the (n,2n) and (n,p) processes compete, there is no experimental information. At low energies (< 2.5 MeV), the ENDF/B-V evaluation seems inadequate and there are no experimental data. Furthermore, above ≈ 15.0 MeV the experimental data are quite sparse. Consequently, it was necessary to rely to some extent on nuclear-model estimates and subjective judgments in the evaluation. ENDF/B-V was generated by combining an eyeguide through the data of Smith and Meadows[111,112] below 10.0 MeV with the results of nuclear-model calculations at higher energies. The result is not representative of the data now available in the vicinity of 14.0 MeV and, therefore, does not provide guidance for the present evaluation.

The code GMA[3] was employed in order to provide a rational method for merging the objective (experimental) and subjective (models and systematics) information in the present evaluation. The subjective information was introduced in the form of a hypothetical data set consisting of points taken from a curve generated in the following manner: Below 2.5 MeV, the nuclear-model code CADE[44] was used to calculate a shape which was then normalized to ENDF/B-V at 3.0 MeV, a region where the latter evaluation represents the data of Smith and Meadows quite well. Above 13.0 MeV, it was found that the shape of the cross section calculated with the code ALICE[43] was representative of the available data in that region, even though the normalization was not consistent with the measured values. Since higher-energy results obtained with CADE were inconsistent with the measured values in both shape and normalization, they were not used. Therefore, the hypothetical data set above 13.0 MeV was constructed by normalizing the ALICE results to the measured values in the vicinity of 14.0 MeV, where the experimental data are both definitive and in reasonable agreement. The region from 2.5 to 10.0 MeV appears to be reasonably described by ENDF/B-V, so the hypothetical data set was taken from that evaluation. Objective information is not available in the 10.0 to 13.0 MeV region. However, systematic information places constraints on the behavior in this region. Therefore, the hypothetical values between 10.0 and 13.0 MeV were taken from

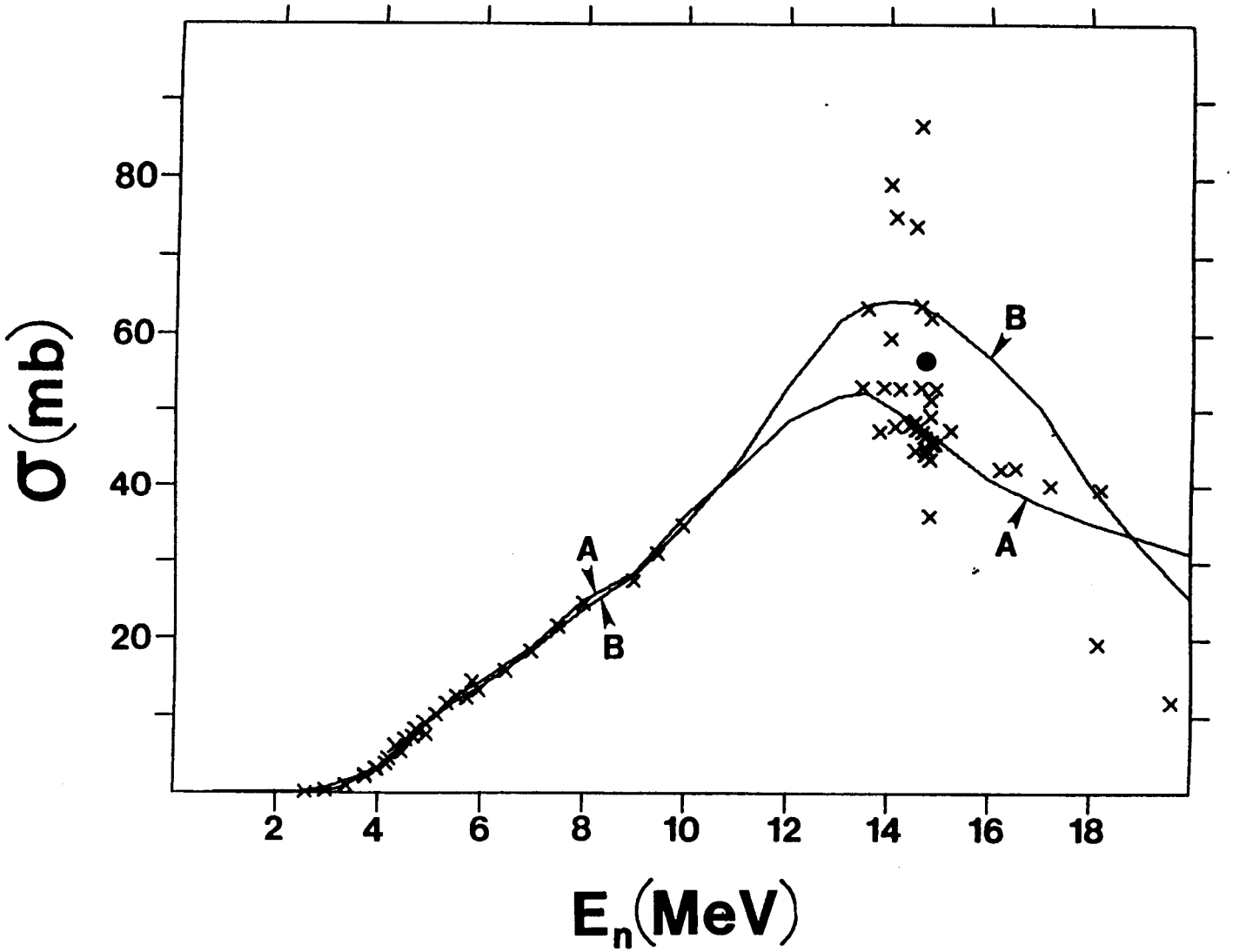

Fig. 14. Experimental data (X) and evaluated cross sections for the ^{59}Co(n,p) reaction. All available experimental data are plotted after applying the necessary adjustments described in the text. Authors and uncertainties are omitted for clarity. The present evaluation is indicated by curve "A", that of ENDF/B-V by curve "B", and the 14.0 MeV evaluation of Evain et al.[64] by the (●) data point.

a smooth curve joining the lower (< 10.0 MeV) and higher (> 13.0 MeV) regions. The assumed shape of this interpolated curve reflects the knowledge that the onset of the (n,2n) process competes with the (n,p) process for the available reaction strength in this region. These hypothetical values were given large errors (≈ 20%), which reflect the probable uncertainties in those regions devoid of experimental information, and which are large enough so that the impact of the hypothetical values is minimal in those regions where objective experimental information is available. A correlation of 50% was introduced for this hypothetical set to insure that the values introduced by this method would carry both shape and normalization information into the least-square evaluation procedure of GMA.

A few experimental data points were rejected as inconsistent, particularly near 14.0 MeV, but most measured values were retained for the analysis. The GMA evaluation generated on the first pass was quite reasonable, considering the information available. The results were accepted for the evaluation up to 13.5 MeV without alteration. At higher energies there were some fluctuations in the evaluated results which were not significant within the errors of the evaluation. Therefore, some cosmetic adjustments were made in generating the final cross-section representation above 13.5 MeV. The final evaluation is reasonably consistent with the shape predicted by the data of Williams et al.[115] and with the shape given by the ALICE calculations, while at the same time reflecting the well-established normalization in the vicinity of 14.0 MeV. The final result is consistent with the explicit GMA values to within uncertainties at all energies. The errors and correlations derived from the least-squares GMA procedures were accepted for the evaluation without adjustment because they appear to reasonably reflect the uncertainty in the vicinity of 14.0 MeV where the cross section is well established from experimental observations.

The final evaluation is shown in Figs. 14 and 15 (the above-described hypothetical values are not plotted in this figure). It is interesting to note that the evaluated results of Evain et al.[84] differ significantly from the present values in the vicinity of 14.0 MeV. There is a good explanation for this effect. The earlier work (Ref. 84) was completed in 1984. Since that time, several precise data sets have been reported in the 14.0 MeV region, each with lower values than the earlier work and with good consistency. This new information has had a significant impact on the present evaluation. It should be noted, however, that the evaluation of Evain et al. carried a large error owing to the wide scatter of the experimental results available at that time, so this value is still consistent with the present work. The present evaluation is also consistent with ENDF/B-V up to 11.0 MeV, since both are based upon the same experimental information. However, there are noticeable differences between the two evaluations at higher energies. Any significant improvement in this section of the evaluation will require new and precise experimental information, particularly in the regions 10.0 to 14.0 MeV and above 15.0 MeV. The requisite measurements are experimentally practical.

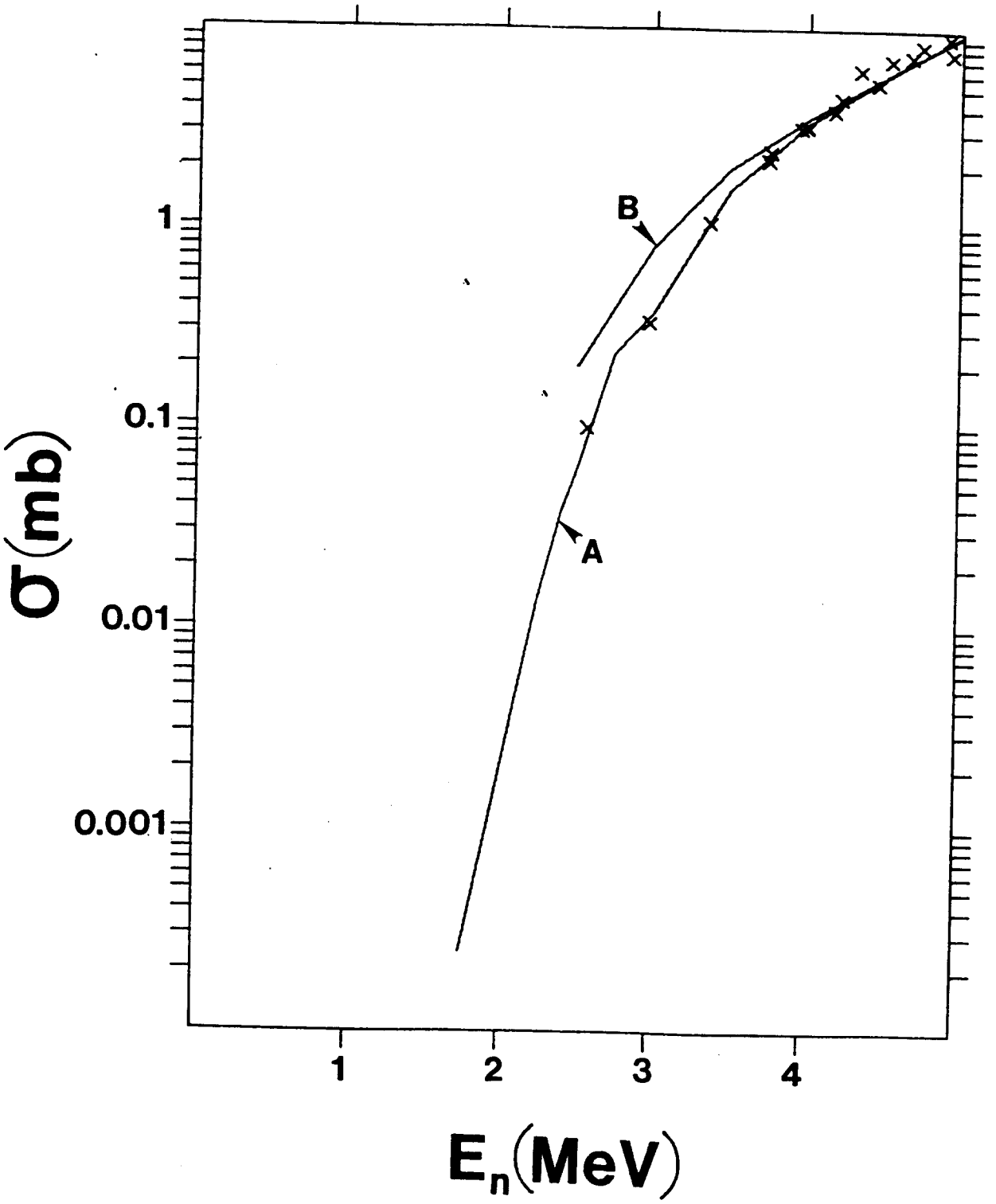

Fig. 15. Experimental data of Smith and Meadows (X)[111:112] and the evaluated cross sections of the ^{59}Co(n,p) reaction below 5.0 MeV. Errors are omitted for clarity. Curves indicate evaluations, with A equal to the present evaluation, and B equal to that of ENDF/B-V.

IX. OTHER PARTICLE-EMITTING REACTIONS

A. General Considerations

The reactions considered in this section, including information about the Q-values and reaction products, appear in Table 4. Note that for multi-particle emission processes we have employed the notation conventionally used in multi-step models to distinguish the order of emission of the particles (e.g., (n,p) indicates that the neutron is first emitted and then the proton, and (p,n) identifies the opposite order).

The available experimental data for these reaction processes is sparse;[7] consequently, the evaluations provided in this work are heavily dependent upon nuclear model calculations. In those instances where some relevant data are available, they have been used to adjust the normalizations for the excitation functions derived from the nuclear model calculations, but generally not their shapes.

Two distinct nuclear model codes were used in these calculations: CADE,[44] a multi-step compound-nucleus model code which employs the Weisskopf-Ewing[45] assumption in the calculations, and ALICE,[43] a statistical code which also employs the Weisskopf-Ewing assumption but includes, in addition, a precompound contribution. In each instance, the parameter sets used in the calculations are the default values suggested by the authors. No attempt has been made to adjust any of the parameters of these models to improve the agreement with specific reaction data sets. In order to obtain some indication of the reliability of results obtained using these codes, corresponding values predicted by them have been compared. Furthermore, for those reactions for which ample data are available (in particular, for dominant and/or well-known processes such as the (n,2n), (n,p) and (n,α) reactions), comparison has been made between experimental data and the model-calculated results. Ultimately, only the results from code CADE were employed in preparing this section of the evaluated file.

For the (n,2n) reaction, the agreement well above threshold between CADE and ALICE is within 20-30% up to 20 MeV, as described in Sec. V. Agreement between the available data and the nuclear model results is of comparable quality. For the (n,p) reaction, the agreement between CADE and ALICE is closer than a factor of two over much of the energy range well above threshold, but becomes progressively poorer at higher energies. The difference at higher energies can be attributed to the fact that the CADE results decrease too sharply with increasing energy owing to a neglect of precompound effects, a well-known phenomenon for the (n,p) reaction. Well above threshold, the agreement between CADE and ALICE is within 20-30% over much of the energy range for the (n,α) reaction. Agreement for the other weaker or multi-particle emission reactions considered in this section is considerably poorer, with differences between a factor of two and more than an order of magnitude routinely observed. Unfortunately, it is for these reactions that we are forced to rely heavily on the results of models. Consequently, in those instances where there are no data available to guide the normalization of the evaluations, the uncertainties are commensurately large.

Table 4. Q-values and reaction products for $^{59}Co(n,X)$ processes.

Reaction	Q-Value(MeV)	Product Nucleus	Half Life*	Decay Mode*
(n;np+pn)	-7.364	Fe-58	Stable	NA
(n;nd+dn)	-15.183	Fe-57	Stable	NA
(n;nt+tn)	-16.573	Fe-56	Stable	NA
(n;nα+αn)	-6.942	Mn-55	Stable	NA
(n;2p)	-12.904	Mn-58	65.3 s	β-
(n;pα+αp)	-8.764	Cr-55	3.497 m	β-
(n;2α)	-7.566	V-52	3.75 m	β-
(n;d)	-5.139	Fe-58	Stable	NA
(n;t)	-8.927	Fe-57	Stable	NA
(n;He-3)	-11.600	Mn-57	1.45 m	β-

* Ref. 85.

Clearly, the uncertainties associated with the evaluations developed for the reactions in this section are difficult to quantify. Therefore, no File 33 covariance information is provided.

B. The (n;n,d + d,n) Reaction

No experimental data were found in the literature[7] for this reaction, so the evaluation is based entirely on nuclear model calculations. In CADE, the (n,d) and (d,n) emission processes are distinguished, but the distinction is not preserved in the present file which consists of the sum of these two components. The (d,n) channel dominates at all energies from threshold to 20.0 MeV, with the (n,d) channel contributing a maximum of about 2% of the reaction yield at 20.0 MeV. The total (n,d) + (d,n) cross section is fairly small (attaining a maximum value of about 2 mb at 20.0 MeV), and the present evaluation is quite uncertain. This process is of little practical concern for applications. Therefore, the resulting neutron-emission spectra are approximated with a simple temperature representation. There is no comparable file in ENDF/B-V.

C. The (n;n,t + t,n) Reaction

No experimental data were identified in the literature[7] for this reaction; in fact, it is, for all practical purposes, an unmeasurable quantity. Therefore, the present evaluation is based entirely on nuclear model calculations. In CADE, the (n,t) and (t,n) emission processes are distinguished, but the distinction is not preserved in the present file which consists of the sum of these two components. The (t,n) channel dominates from threshold to 20.0 MeV, with the (n,t) channel contributing less than 0.8% of the reaction yield at all energies. The total (n,t) + (t,n) cross section is very small (less than 22 μb at all energies), and the uncertainty in the present evaluation is large. Although the reaction contributes to accumulation of tritium activity in structural materials containing cobalt, the yield from this process is overwhelmed by the (n,t) reaction and so is of little applied consequence. Again, the resulting neutron-emission spectra are approximated by a simple temperature formalism. There is no equivalent file in ENDF/B-V.

D. The (n;n,α + α,n) Reaction

This reaction leads to the production of stable ^{55}Mn; however, the cross section can, in principle, be deduced experimentally by comparing the total measured α-production with the production of active ^{56}Mn via the well-known (n,α) reaction, since no other α-production reactions are of any importance below 20.0 MeV. Several comparable (n;α,X) cross section values have been reported in the literature.[7] This information has been reviewed by Kneff et al.[123] These results correspond to neutron energies in the vicinity of 14.0 MeV, with reported values in the range 33 to 59 mb. Kneff et al. have employed mass spectrometric methods to measure α-accumulation in pure cobalt samples irradiated with 14.8-MeV neutrons. This carefully performed

experiment yielded the value (40 ± 3) mb for the total α-production cross section. Since the earlier data are widely discrepant with respect to the quoted errors, and the result of Kneff et al. falls near the middle of the range of earlier results, we have accepted the value from this most recent experiment. Subtracting the (n,α) cross section (30 mb from the present evaluation) yields the result (10 ± 3) mb. Thus, this reaction contributes a substantial portion (≈ 25%) of the total α-production in cobalt at primary fusion-neutron energies. This process finally becomes the dominant mechanism for α-production above 16.0 MeV, according to predictions from model calculations. Owing to the role of α-production in fast-neutron radiation damage, and to the significant contribution from this reaction in this respect, it is of considerable importance for applications. Above threshold, the cross-section shapes predicted by the codes CADE and ALICE are in qualitative agreement. At 14.8 MeV, the calculated total nα + αn cross section given by CADE is 6.4 mb, in fair agreement with experiment. Therefore, the present evaluation was generated by renormalizing the CADE results to the experimental value at 14.8 MeV, as indicated above. Two channels are treated in the calculations, namely, (n,α) and (α,n). The yield from the (α,n) channel is about a factor of seven larger than the (n,α) channel near 14.0 MeV, but the yields from the two channels become roughly comparable at 18.5 MeV, and the (n,α) component ultimately dominates at higher energies up to 20.0 MeV. The present evaluated file consists of the sum of these two components. In view of the preceding discussion, the uncertainty of this evaluation well above threshold is probably on the order of 50%, with substantially larger uncertainties to be expected near threshold. The corresponding neutron-emission spectra are presented as discrete-point distributions with assumed angular isotropy. These distributions were constructed as a part of the neutron-emission considerations discussed in Sec. IV, above. The comparable ENDF/B-V cross sections are considerbly smaller throughout the energy range (e.g., by a factor of 4-5 near 14.0 MeV), and do not show the broad maximum of the present evaluation near 17.0 MeV.

F. The (n,2p) Reaction

No experimental data were found in the literature[7] for this reaction, though, in principle, measurements could be made by observing γ-ray emission associated with the beta decay of ^{56}Mn.[86] The predictions from codes CADE and ALICE differ by no less than a factor of 30 at 20.0 MeV, and by orders of magnitude near threshold, with the ALICE values exceeding those from CADE at all energies. The present evaluation is based entirely on model-calculated results from CADE, but the content of this file must be viewed as highly speculative in view of the obvious lack of any reliable information for this process. In any event, the cross section appears to be quite small (probably considerably less than 1 mb at 20.0 MeV), so this reaction is of no particular applied interest. There is no comparable file in ENDF/B-V.

G. The (n;p,α + α,p) Reaction

No data are reported in the literature[7] for this reaction. The reaction product, ^{55}Cr, is beta active, but decay is predominantly to the ground state

of ^{55}Mn and few γ-rays are emitted.[86] Consequently, measurements of this cross section would be very difficult, if not impossible. The present evaluation relies on the results of model calculations. The predictions of ALICE and CADE differ by roughly an order of magnitude over most of the energy range above threshold, with CADE predicting the larger values. Contributions from the (p,α) and (α,p) channels appear to be comparable over the entire energy range from threshold to 20.0 MeV. The present evaluation consists of their sum. The total (p,α) + (α,p) cross section is very small (probably less than 50 μb at 20.0 MeV). Results from CADE have been accepted for the present evaluation, though they are clearly quite speculative in view of the absence of reliable information. This reaction is of little apparent applied concern. There is no comparable file in ENDF/B-V.

H. The (n,2α) Reaction

The (n,2α) reaction leads to ^{52}V, which can be measured by observation of gamma rays emitted following beta decay.[85] However, the cross section for this process is extremely small and no experimental values have been reported.[7] Calculated values were only obtained with code CADE, and these are used for the present evaluation. The results are highly speculative, but, in view of the fact that the predicted cross sections below 20.0 MeV are smaller than 1 μb, this process is of no apparent practical importance. There is no comparable file in ENDF/B-V.

I. The (n;n,p + p,n) Reaction

This reaction is of significant concern in the context of the present evaluation, as is evident from the following discussion. The evidence from both experimental and theoretical studies indicates that this process provides a significant fraction of the total proton emission yield at energies of interest for fusion applications. Furthermore, hydrogen production is a source of concern because of its role as an important radiation damage mechanism for structural alloys, several of which contain cobalt.

Experimental determinations of the cross section are difficult. The reaction product is ^{59}Fe, which is stable. Most of the available data on the cross section have been deduced by direct detection of the emitted protons.[112,116,117,124,125] All of these results are at 14.1 MeV. The experiments have used either nuclear-emulsion or counter-telescope methods. In these measurements, protons with energies lower than 2-3 MeV are generally not observed, so there is a tendency for underestimation of the cross section unless corrections are applied, particularly of the (n;p,n) component, since it appears that a significant portion of the yield for this process involves relatively low energy protons. In general, interpretation of the data is difficult because protons from the (n;p) and (n;n,p + p,n) reactions can be distinguished only through indirect arguments concerning presumed differences in the shapes of the proton energy spectra for these processes. The details are described in the referenced papers. To date, estimates of the (n;n,p + p,n) cross section deduced from these experiments have been

qualitative at best. The derived (n;n,p + p,n) cross section values appear to be in the range 11-60 mb. One interesting data set has been reported from measurements of γ-ray yield associated with de-excitation of levels in ^{58}Fe, which are excited by the (n;n,p + p,n) as well as the (n,d) reaction.[126] The latter contribution is known to be considerably smaller than the former, so it will be overlooked for present purposes. In this particular experiment, it was observed that only two states in ^{58}Fe appear to be strongly excited through the (n;n,p + p,n) process, namely, the 811-keV first-excited state and the 2077-keV state. Most of the de-exciting γ-ray transitions pass through the 811-keV level, so observation of the yield of the 811-keV γ-ray provides a good estimate of that portion of the total reaction cross section which involves the excited states of ^{58}Fe.[96] These measurements cover the range ≈ 16-22 MeV in incident neutron energy. Over this range, the cross section for production of 811-keV γ-rays increases from ≈ 50 mb to ≈ 150 mb. Unfortunately, this approach provides no information about the contribution due to production of ^{58}Fe in the ground state.

Since there was little experimental information available, and that at only one energy, we were forced to rely on nuclear model calculations for estimates of the energy-dependent shape of the cross section from threshold to 20.0 MeV. Calculations were performed in three distinct ways, as described below. First, the computer code CADE was used, with default parameters for the optical potentials and level densities from Brancazio and Cameron,[46] to compute the (n;n,p), (n;p,n), and (n,d) components separately. The results of CADE indicate that the (n;n,p) process dominates to a great extent, particularly near threshold. Of the remaining two processes, the (n,d) is the smallest by far. Therefore, we are essentially concerned here with a mechanism consisting of neutron emission followed by subsequent proton emission. The combined (n;n,p + p,n) cross section computed with CADE rises steadily above threshold, reaching a maximum of ≈ 200 mb near 12.0 MeV. At higher energies it drops, owing to competition from (n,2n). The calculated results are much larger than the experimental values at 14.1 MeV. Next, the code ALICE was used, with default parameters, to compute the combined (n;n,p + d) cross section, or equivalently the production of ^{58}Fe. The cross sections from ALICE were very much smaller than those obtained using CADE, and the energy-dependent behavior was quite different. The cross section was found to increase steadily with energy from threshold to 20.0 MeV. The onset of the (n,2n) process appeared to have no influence. The computed cross sections were smaller at 14.1 MeV than indicated by experiment. Our initial preference was to employ the results from ALICE for the purpose of the present evaluation because, unlike CADE, it includes precompound processes and also provides the spectra of particles emitted from the individual excited nuclei. However, it was observed early on that ALICE appeared to have difficulty in handling the (n;n,p) process. The initial emission of a neutron leaves the excited nucleus, ^{59}Co, with the following separation energies for particle emission: neutron, 10.454 MeV; proton, 7.364 MeV; alpha particle, 6.943 MeV; deuteron, 15.184 MeV. Thus, there is a range of excitation energies about 3 MeV wide where only proton, alpha-particle, and γ-ray emission are energetically possible. At particle energies of about 3 MeV, alpha-particle emission is not very competitive with proton emission because of coulomb-barrier effects, and γ-ray emission does not become very competitive with proton emission until the proton energy is less than 1.0

MeV. The cross section for emission of a first neutron is rather substantial, and a significant portion of this strength must end up in the channel in which a proton is subsequently emitted. On the basis of these considerations, the (n;n,p) cross section is likely to be substantial. These considerations did not appear to be reflected in the ALICE results. Finally, a hybrid set of calculations was performed. Since ALICE included the precompound process, it was used for the first stage of the reaction to give the spectra of the first particle emitted. The distribution of excitation energy in the residual nuclei was then inferred from these spectra, and CADE was used to calculate the subsequent stage. It was found that the resulting cross section at 14.0 MeV was 190 mb, much larger than the experimental values derived from proton spectra.

In summary, we have no reliable information on this reaction. There are experimental data for proton emission at a single energy that indicates a cross section in the vicinity of 50 mb. However, the energetics of the reaction suggest that there will be a large number of low-energy protons emitted that are likely to be below the threshold for proton detection. Thus, the proton-spectrum measurements at 14.0 MeV may be missing a major part of the (n;n,p) branch. It is our intuitive feeling that the cross sections are high but, in view of the paucity and uncertainty of the experimental data, the results of the hybrid calculations were used in this evaluation. Our confidence in the results is not high, either with regard to the shape or the normalization. An uncertainty of more than a factor of two is very possible.

J. The (n,d) Reaction

This process shares many common features with the (n;n,p + p,n) reaction, though the kinematic threshold is somewhat lower in energy. Only one data set has been reported, namely, the results of Colli et al.[126,127] at 14.0 MeV. These authors measured a deuteron spectrum at 14° emission angle relative to the incident neutrons. Levels up to ≥ 4 MeV in ^{58}Fe were populated in the process. The cross section was determined to be 0.15 (± 30%) mb/sr from this work; however, no indication is provided in the references as to whether this value includes an estimated contribution from deuteron energies below the experimental cutoff. Furthermore, the (n,d) reaction appears to proceed largely via the direct proton pickup mechanism, which would suggest the likelihood of rather anisotropic (forward peaked) deuteron emission. However, no data are available at other angles to support this contention. If isotropy is assumed (which probably overestimates the angle-integrated cross section), the value 1.9 mb is obtained for 14.0 MeV. Calculated values are available from the code CADE. The agreement at 14.0 MeV is qualitatively rather good. For this reason, these calculated values are accepted without alteration for the present evaluation. The errors are obviously large, probably corresponding to an uncertainty of at least a factor of two in the cross section; however, since the cross section is modest (< 6 mb at 20.0 MeV), this reaction process is of relatively little applied significance. The present evaluation is consistently larger than that of ENDF/B-V, but the difference is well within the respective uncertainties.

K. The (n,t) Reaction

This reaction is of interest in fusion energy systems because it is the principal tritium-producing reaction in cobalt, a constituent of ferrous-based alloys which may eventually be used in fusion reactor systems. The reaction product is ^{57}Fe, which is stable, so measurements are based on detection of the low-energy beta activity associated with the decay of tritium. An estimate of the 14-MeV cross section for this reaction was first published by Poularikas and Gardner,[128] but their suggested value of (19 ± 14) μb appears to be much too low relative to the more recent results of Khurana and Govil,[129] Csikai et al.,[130,131] and of Qaim et al.[132,133] The shape of the excitation function computed with code CADE is in excellent agreement with that deduced from the cross sections of Qaim et al. in the 16-19 MeV range; however, the magnitudes of the calculated values are lower than the experimental ones by about a factor of three in this range. Therefore, the present evaluation employs the results calculated using CADE, renormalized to agree with the recent relatively precise data of Qaim et al. (see Fig. 16). The data of Khurana and Govil and of Csikai et al. near 14.0 MeV appear, on the basis of systematic considerations, to be too large when compared with the present evaluation, but it should be kept in mind that the shape of the calculated cross section for this energy region is quite speculative, owing to the presence of strong competition from other reaction channels. The value suggested by Poularikas and Gardner does indeed appear to be much too low. The estimated uncertainty in the present evaluation may well be as low as ≈ 10-15% in the region from 16-20 MeV, i.e., comparable to the uncertainies in the data of Qaim et al. However, at other energies, especially toward threshold, the uncertainty is surely much greater. In particular, knowledge of the tritium production cross section in the vicinity of 14.0 MeV, which is important for fusion applications, must be considered as quite unsatisfactory. The present evaluated cross sections are several orders of magnitude larger than that of ENDF/B-V.

L. The (n,^{3}He) Reaction

The product nucleus from this reaction is ^{57}Mn, which decays via beta emission, followed by a few characteristic γ-rays.[86] Although in principle the cross section can be measured via the activation method, the combination of small cross section and short half life conspire to make this a very difficult task. Several experimental cross section values (or upper limits, in some instances) near 14.0 MeV have been reported in the literature.[67,134–138] As can be seen from Table 5, the spread in these reported values is so large (more than two orders of magnitude!) that one is led to suspect that some, if not all of these data may be afflicted by some unidentified contamination or background effects.

The cross sections calculated with code CADE increase with neutron energy from ≈ 0.01 μb (minimum cross section provided by CADE) at 16.0 MeV to ≈ 5 μb at 20.0 MeV. These values are lower by orders of magnitude than even the smallest result from Table 5. However, since the available experimental data provide conflicting cross-section magnitudes, the present evaluation is based entirely on results computed with code CADE. The reliability is

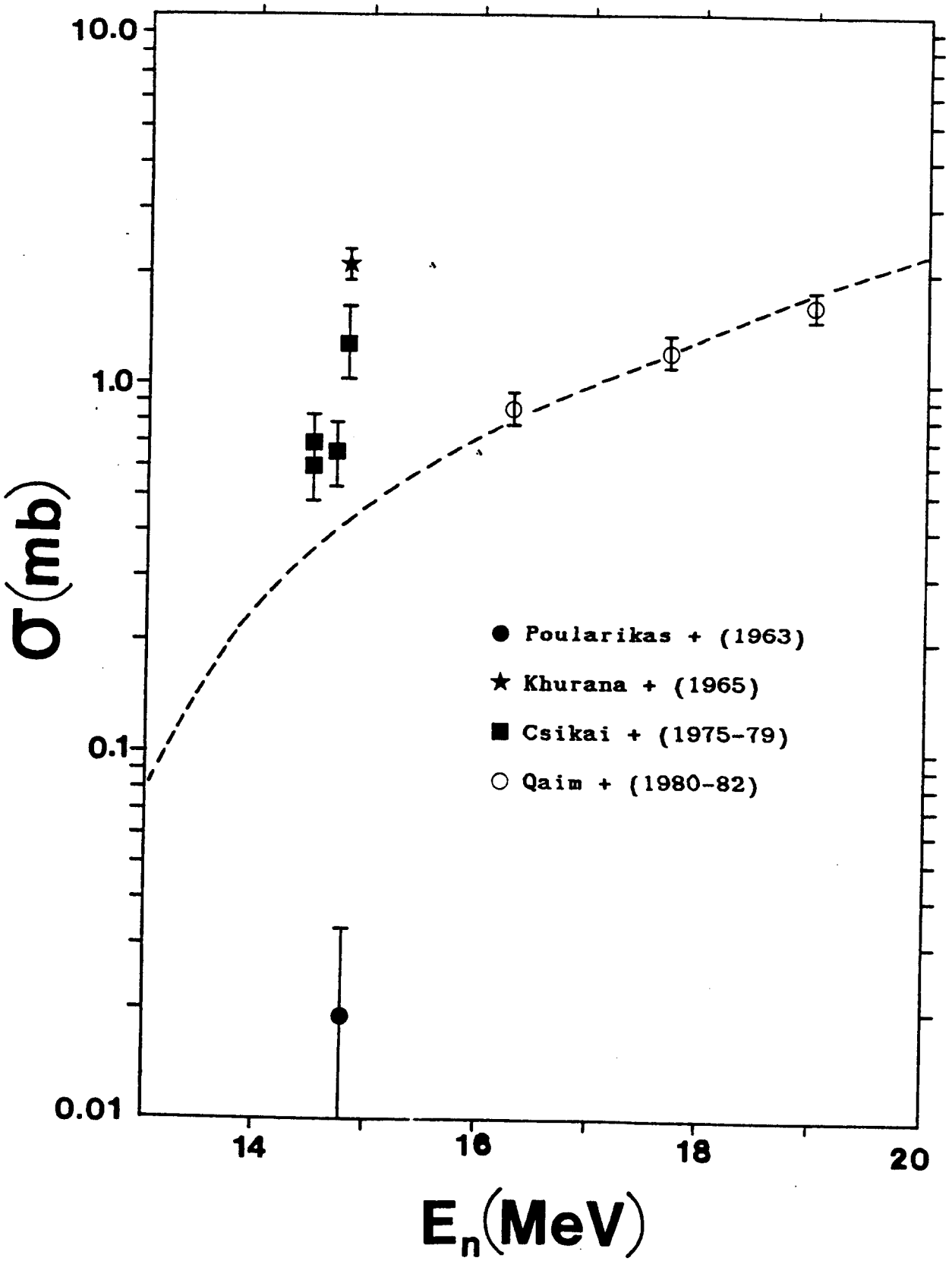

Fig. 16. Comparison of measured and evaluated $^{59}Co(n,t)^{57}Fe$ cross sections. Curve indicates the result of the CADE calculation which forms the resent evaluation. Data symbols indicate measured values, as discussed in the text.

Table 5. Various experimental values for the $^{59}Co(n,^{3}He)$ cross section.

Author	Ref.	Energy (MeV)	Reported Cross Sec.
Kumabe et al. (1960)	134	14.8	< (1-3) mb
Bramlitt et al. (1962)	135	14.5	< 0.1 mb
Frevert et al. (1965)	136	14.8	< (17 ± 8.5) μb
Qaim et al. (1974)	137	14.6	(4.7 ± 2.2) mb
Diksic et al. (1974)	138	14.6	(62 ± 30) μb
Bahal et al. (1984)	67	14.7	(10.4 ± 0.6) μb

obviously very low, so it is fortunate that this process appears to be of little applied concern. The present evaluation is about a factor of five larger than those of ENDF/B-V, but both are very speculative.

X. PHOTON PRODUCTION

The photon-production data are made up of contributions from (n,γ), (n;n',γ), and a continuum from all other photon-production reactions.

Photon production for the (n,γ) reaction is represented by 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.[140] at thermal neutron energy. The average energy of the spectrum was determined and divided into the Q-value for the reaction in order to determine the low-energy photon multiplicity. The same spectrum was used at 20.0 MeV with the multiplicity adjusted to conserve energy.

Warren's code CASCADE,[141] which incorporates the method used in Reffo's BRANCH[142] code, was used to determine the energy-dependent cross sections for the specific photons resulting from de-excitation of the levels excited by inelastic neutron scattering.

For all other reactions, the photon-production cross sections and spectra were calculated using the R-Parameter formalism of Perkins et al.[143] The R-Parameter formalism requires formal representation of energy distributions for all secondary particles (i.e., charged-particles as well as neutrons) in order to calculate the photon-production cross sections and spectra. Since 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 "global" R(U) values of Ref. 143 were used for the calculations.

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

XI. SUMMARY

A comprehensive evaluated neutronic data file for elemental cobalt (100% ^{59}Co) has been described, and the corresponding numerical values transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. This file is believed to be a considerable improvement over that of ENDF/B-V in a number of areas, and should be suitable for the large majority of fusion- and fission-applications involving neutronic design. Of necessity, there are compromises due to the limited availability and frequent poor quality of experimental data, the suitability of relevant models, and restrictions of

the ENDF/B format system. These compromises may make the general file less than optimal for some special applications. In those instances, users are encouraged to seek out special purpose files tailored to their needs.

Substantive further improvement of the file will require some fundamentally new information. Particular problem areas involving such new endeavors are:

1. A comprehensive study of the resonance region is warranted. This should include reinterpretation of the best available experimental information and, as warranted, new measurements to provide improved definition.

2. Neutron total cross sections are limited and discrepant above about 15.0 MeV. At least one precise data set at these higher energies is desirable.

3. There appears to be no experimental knowledge of neutron elastic scattering in the 10.0 to 20.0 region, and the present file had to rely entirely on a model extrapolation in this area. It is a region where the model can be expected to change, and where good knowledge of elastic scattering is essential if the important nonelastic cross section is to be well determined. For improvement, several good differential elastic scattering measurements are desirable, distributed between ≈ 10.0 and 20.0 MeV at ≈ 2.0 MeV intervals. Such measurements are feasible.

4. Experimental knowledge of the inelastic-neutron excitation cross sections above about 4.0 MeV is inadequate and should be improved by some detailed measurements distributed between 4.0 and 10.0 MeV. In addition, detailed measurement of inelastic-scattering excitations in the lower-energy fluctuating region would be useful. Both of these efforts are feasible, but difficult.

5. Continuum neutron-emission spectra should be obtained at a number of energies between 8.0 and 20.0 MeV. The measurements should be carefully correlated with calculational interpretations, with the objective of model validation since the models must ultimately be used to provide the individual components of the evaluation. The measurements should particularly extend across the prominent reaction thresholds (e.g., about the (n,2n) and (n;n,p) thresholds). Both spectra and angular distributions are desired. In addition, general information dealing with the improved definition of statistical level parameters is highly desirable. Concurrent with the above measurement effort, attention should be given to modeling capability, with the objective of resolving the obvious discrepancies between results calculated with different models and/or codes.

6. Energy-averaged neutron capture cross sections should be measured with relatively broad resolution from ≈ 0.1 to 5.0 MeV, using both direct γ-ray detection and activation methods. The current experimental data base is no more than qualitative. The measurements will be difficult due to the small magnitude of the relevant cross section, but they are feasible.

7. (n,p) cross sections should be measured with good accuracy between 10.0 and 13.0 MeV and above 15.0 MeV. This potential dosimetry cross section should be far better known. The measurements are feasible, though the energy ranges of interest are difficult to reach with existing neutron sources.

8. Photon-production cross sections and spectra should be measured from ≈ 1.5 to 20.0 MeV, with monoenergetic sources where possible. The current paucity of experimental data makes it impossible to check any calculated data, other than to ensure conservation of energy.

Most of the above needs imply measurements with monoenergetic neutron sources.

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