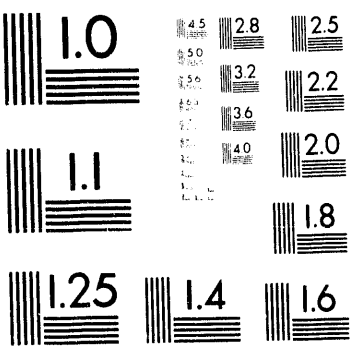
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ANL/NDM-129

EVALUATED NUCLEAR DATA FILES FOR THE NATURALLY-OCCURRING ISOTOPES OF CADMIUM*

by

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Keywords

Comprehensive evaluated neutronic evaluated data files for the naturally-occurring isotopes of cadmium.
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EVALUATED NUCLEAR DATA FILES FOR THE NATURALLY-OCCURRING ISOTOPES OF CADMIUM*

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ABSTRACT

Comprehensive neutronic evaluated data files for the naturally-occurring isotopes of cadmium are deduced from experimental data and nuclear models, and presented in the ENDF/B-VI formats. Particular attention is given to those processes relevant to fuel-cycle and fission-product applications. Comparisons are made with prior evaluations of the cadmium isotopes, and discrepancies and consistencies cited. Some of the discrepancies are very large (e.g., as much as 100%), and the differences have the potential for a pronounced impact on applications usage. The present files are comprehensive, including may important processes that are not represented in the contemporary ENDF/B-VI system. Recommendations are made for future measurements where appropriate.

TABLE OF CONTENTS

I. INTRODUCTION

Shortly after Chadwick's discovery of the neutron [Cha32], Fermi and coworkers observed that some elements have very large slow-neutron absorption cross sections. Prominent of these is cadmium, and the metal has been widely used as a neutron absorber ever since. The first reactor (CP-1) employed cadmium control rods half a century ago. More generally, cadmium has found wide use in a range of control, shielding and detector applications. Moreover, the isotopes of cadmium are fission products, and thus their neutronic properties influence fuel-cycle and fuel-processing considerations. With this broad technological relevance of cadmium, one would have thought that the neutronic properties of the isotopes of cadmium are well known. In fact, the low-energy resonance properties of the cadmium isotopes are reasonably established [MDH81]. However, only recently has there been much attention to the high-energy neutron reaction with the cadmium isotopes [SG92]. It is the objective of this work to use this new information, and that previously reported in the literature, to construct comprehensive evaluated neutronic files for the isotopes of elemental cadmium, and to present these files in the ENDF/B-VI formats [ENDF]. The results considerably update prior ENDF cadmium files which are old and/or very limited in scope.

Elemental cadmium consists of eight isotopes; ^{106}Cd(natural abundance 1.25%), ^{108}Cd(0.89%), ^{110}Cd(12.49%), ^{111}Cd(12.80%), ^{112}Cd(24.13%), ^{113}Cd(12.22%), ^{114}Cd(28.73%) and ^{116}Cd(7.49%). Each of these isotopes is dealt with in the present evaluations, and the elemental evaluation follows from a weighted average of the isotopic components. The starting point for the evaluations is; i) the experimental data files of the National Nuclear Data Center [NNDC], ii) extensive new experimental information given in ref. [SG92], and iii) models for interpolating and extrapolating the observed physical values. The primary calculational tool is the optical-statistical model code ABAREX [Mol82], supported by the reaction code GNASH [YAC92], and the coupled-channels code ANLECIS [Mol81]. The necessary potential parameters were generally taken from ref. [SG92], with supplementary values as cited in the subsequent sections. Throughout, comparisons are made with measured data where available, and with prior evaluations as appropriate. The methodology is that of horizontal evaluation, enhancing consistency between the various isotopic evaluations.

Subsequent sections of this report deal with: II) resonance parameterizations, III) energy-averaged total cross sections, IV) elastic neutron scattering, V) inelastic neutron scattering, VI) neutron radiative capture, VII) the (n,2n) and (n,3n) processes, and VIII) a variety of (n,X) reactions. Finally, a brief summary is given

in Section IX, including recommendations for future work.

II. RESONANCE PARAMETERIZATIONS

Interpretations in the resonance region are a complex and specialized endeavor. The primary reference is the resonance-parameter compilation of Mughabghab et al. [MDH81], supplemented with the capture resonance studies of Musgrove et al. [Mus+82]. This resonance information is not complete, and extends only to a few keV. Very recently R. Q. Wright has examined the resonance properties of the even isotopes of cadmium, working from the above two primary references [Wri93]. From this study even-isotope resonance-parameter evaluations were obtained. Resonance parameters are given in the multi-level Breit-Wigner formalism, based primarily upon ref. [MDH81], up to ≈ 6 keV. Where there were gaps in the resonance parameters deduced from measurements, statistically reasonable s- and p-wave resonances were inserted in the evaluations. In addition, Wright provides an unresolved-resonance evaluation extending from ≈ 6 keV to 100 keV. The latter gave detailed consideration to the average capture cross sections of ref. [Mus+82]. The Wright even-isotope resonance evaluations have been reviewed by CSEWG [CSEWG], and judged to be as good a quality as can be obtained without additional measurements. Therefore, they were accepted for the present even-isotope evaluations. The details can be found in ref. [Wri93]. For the present odd-isotope evaluations, the resonance parameters of ref. [MDH81] were explicitly used. These extend to ≈ 5 keV. No effort was made to introduce a representation of the unresolved resonance parameters, nor to fill in gaps in the odd-isotope resonance region.

From the study of Wright [Wri93], it is clear that the resolved even-isotope resonances are not completely defined, with several gaps. The same shortfall is doubtless even more valid for the odd-isotopes. Therefore:-

-- Recommendation:- Comprehensive high-resolution resonance measurements of the isotopes of cadmium should be undertaken, assuring complete energy coverage to at least 10 keV.

The problems in the unresolved resonance region are at least as acute. The lowest-energy energy-averaged total cross section value appears to be at ≈ 47 keV, with no experimental knowledge from that energy to the resolved resonance measurements. At least:-

-- Recommendation:- Energy averaged, or partially resolved, total cross-section measurements should be made from a few-keV to 100+ keV.

Such measurements are quite conventional, and should be possible with

good accuracies.

III. ENERGY-AVERAGED TOTAL CROSS SECTIONS

The present isotopic evaluations of the energy-averaged neutron total cross sections of cadmium extend from the upper energy limit of the resonance representations to 20 MeV. There is essentially no known relevant isotopic total-cross-section information in the literature. Thus, the procedure was the formulation of an elemental cadmium total-cross-section evaluation and then the extrapolation of that result to the isotopes using the optical-statistical model of ref. [SG92] and the isovector strengths of ref. [WG85]. All calculations used in this extrapolation were made using the spherical optical-statistical model code ABAREX [Mol82].

There is a reasonable body of experimental elemental cadmium energy-averaged total-cross-section information as given in refs. [PW83], [TL66], [SW54], [VS66], [FG71], [BPS58], [ND54], [Joh+53], [WB55], [GM71], [CGB52], [PBS60], [Hau68], [Wal+53], [Bow+61], and [TW53]. One of these data sets is ten years old, and the remainder more than twenty years old. Despite this antiquity, the data are reasonably consistent. This data base was plotted and a few values that were obviously inconsistent with the body of information were abandoned. The experimental data were then combined. Where a particular set of data had a large number of experimental values (e.g., [FG70] and [VS66]), weighted energy averages of the data were constructed. The lower-energy average displayed some unresolved resonance fluctuations of small magnitude, due to contributions from the various isotopes. As the goal was isotopic evaluations, and it is impossible to determine the various isotopic contributions to such fluctuations, they were ignored. The lower-energy limit of the experimental data was $\approx$ 47 keV, which is above the upper-energy limit of all of the discrete-resonance interpretations. Therefore, it was necessary to use model interpolation over this low-energy void where the unresolved resonance representation of ref. [Wri93] is not available. This extrapolation introduces some added uncertainty as the calculated results are very sensitive to model parameters at low energies.

It is shown in ref. [SG92] that a spherical-optical-model potential gives a reasonable representation of the above experimental total cross sections (see Figure IV-3 of ref. [SG92]). The respective potential parameters are given in Table III-1. Differences between measured and calculated values are limited to $\approx 0 \rightarrow 5\%$. By comparing calculated and measured total cross sections a detailed energy-dependent table of "bias factors" was determined such that the product of the ABAREX-calculated values and bias factors was in agreement with the experimental result to as well as the latter could be determined from the scatter of the measured values. The bias

factors varied in an energy-systematic manner from essentially zero to several percent. These bias factors were retained for use in many aspects of the evaluations, as cited in the subsequent sections.

The elemental results obtained with the above procedures are illustrated in Fig. III-1. The present evaluation gives a very acceptable representation of the experimental data base. It is also significantly different from the elemental cadmium evaluation of ENDF/B-VI [NNDC], as shown in Fig. III-2. Below 15 MeV the differences between the two evaluations vary by up to 5 - 10%, with the larger differences in the few-hundred-keV region of particular applied importance. Above 15 MeV, ENDF/B-VI should not be taken seriously, as it seems to be nothing but a clerical extension of a thirty year old UK evaluation. The uncertainties associated with the present elemental evaluated total-cross-section results are estimated to be $\approx$ 2% below 15 MeV, and possibly somewhat larger at higher energies.

The above elemental evaluation was extrapolated to the isotopic evaluations using the same optical potential and bias factors, but including the effects of real and imaginary isovector potential strengths respectively given by

$$V = V_0 - V_1 \cdot (N-Z)/A$$
$$W = W_0 - W_1 \cdot (N-Z)/A. \qquad \text{(III-1)}$$

Z is clearly 48 for all cases, and the elemental A was taken to be 112.411. V_1 was assumed to be 24 MeV, and W_1 to be 12 MeV, as suggested by global models [WG85]. The model extrapolation was primarily influenced by the $A^{1/3}$ size effect, and secondarily by isovector effects. The calculated total cross sections were adjusted, using the above bias factors, to obtain the individual isotopic evaluated neutron total cross sections. The respective uncertainties are difficult to quantitatively estimate, but the above elemental results suggest that they are in the order of several percent. The various isotopic results are similar, and combine to provide a weighted average that is in good agreement with the above elemental evaluation as shown in Fig. III-3.

In the ENDF/B-VI fission-product file there are a number of isotopic cadmium evaluations. Illustrative comparisons of the ENDF/B-VI and present evaluations are given in Fig. III-4. The discrepancy is largest for ^{106}Cd, where it is $\approx$ 100% at some energies. More typical is the ^{112}Cd example of Fig. III-4 where the

Table III-1. Spherical-optical-model parameters used in the present evaluation. All geometries are expressed in fermis, energies (E) in MeV, and real- and imaginary-potential strengths as volume-integrals-per-nucleon (J) in MeV-fm^3. The potential was derived in the comprehensive physical study of ref. [SG92].

Real Potential (V)[a]

$$J_V = 458.6 - 3.759 \cdot E$$
$$r_V = 1.3023$$
$$a_V = 0.6272$$

Imaginary Potential (W)[b]

$$J_W = 94.6 - 6.801 \cdot E + 0.331 \cdot E^2$$
$$r_W = 1.3790 - 0.01278 \cdot E$$
$$a_W = 0.3485 + 0.0178 \cdot E$$

Spin-Orbit Potential (SO)[c]

$$V_{so} = 6.0588 - 0.015 \cdot E$$
$$r_{so} = 1.103$$
$$a_{so} = 0.560$$

[a] Saxon-Woods form [Hod71].

[b] Saxon-Woods-derivative form [Hod71].

[c] Thomas form [Hod71].

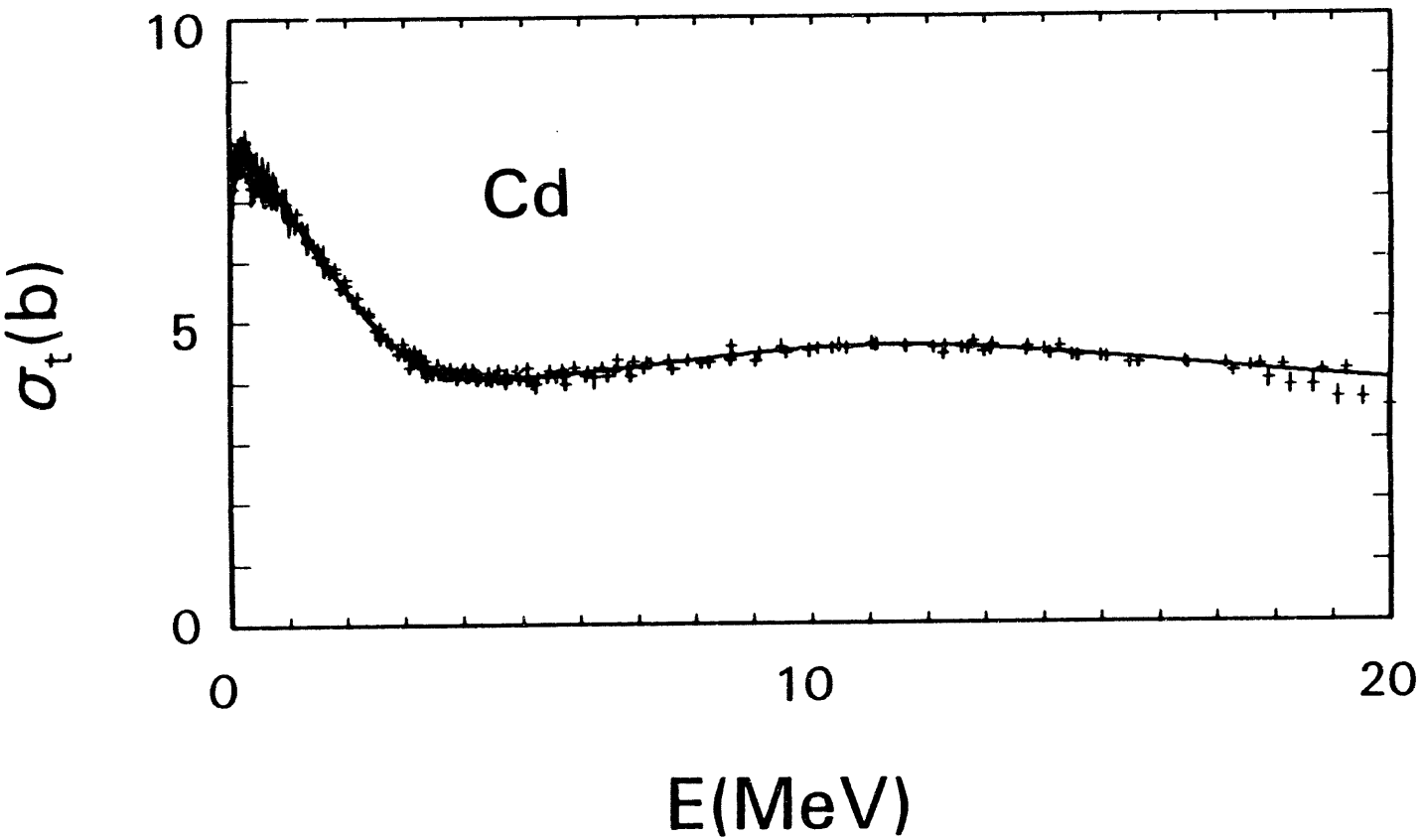

Fig. III-1. Comparison of the present cadmium elemental total cross section evaluation (curve) with the experimental data base (symbols).

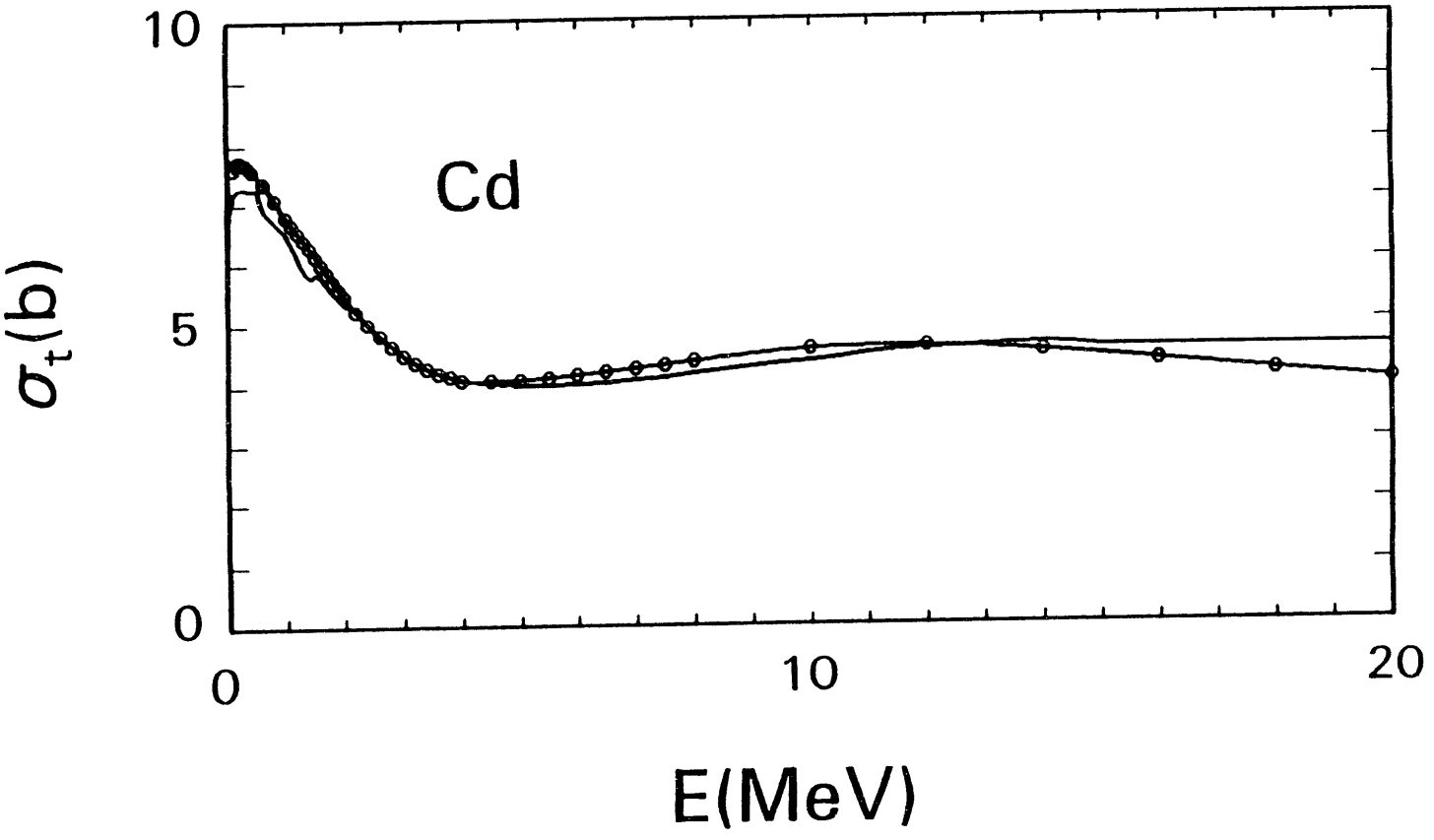

Fig. III-2. Comparison of the present elemental cadmium total-cross-section evaluation (curve with circular symbols) with the elemental ENDF/B-VI evaluation (simple curve).

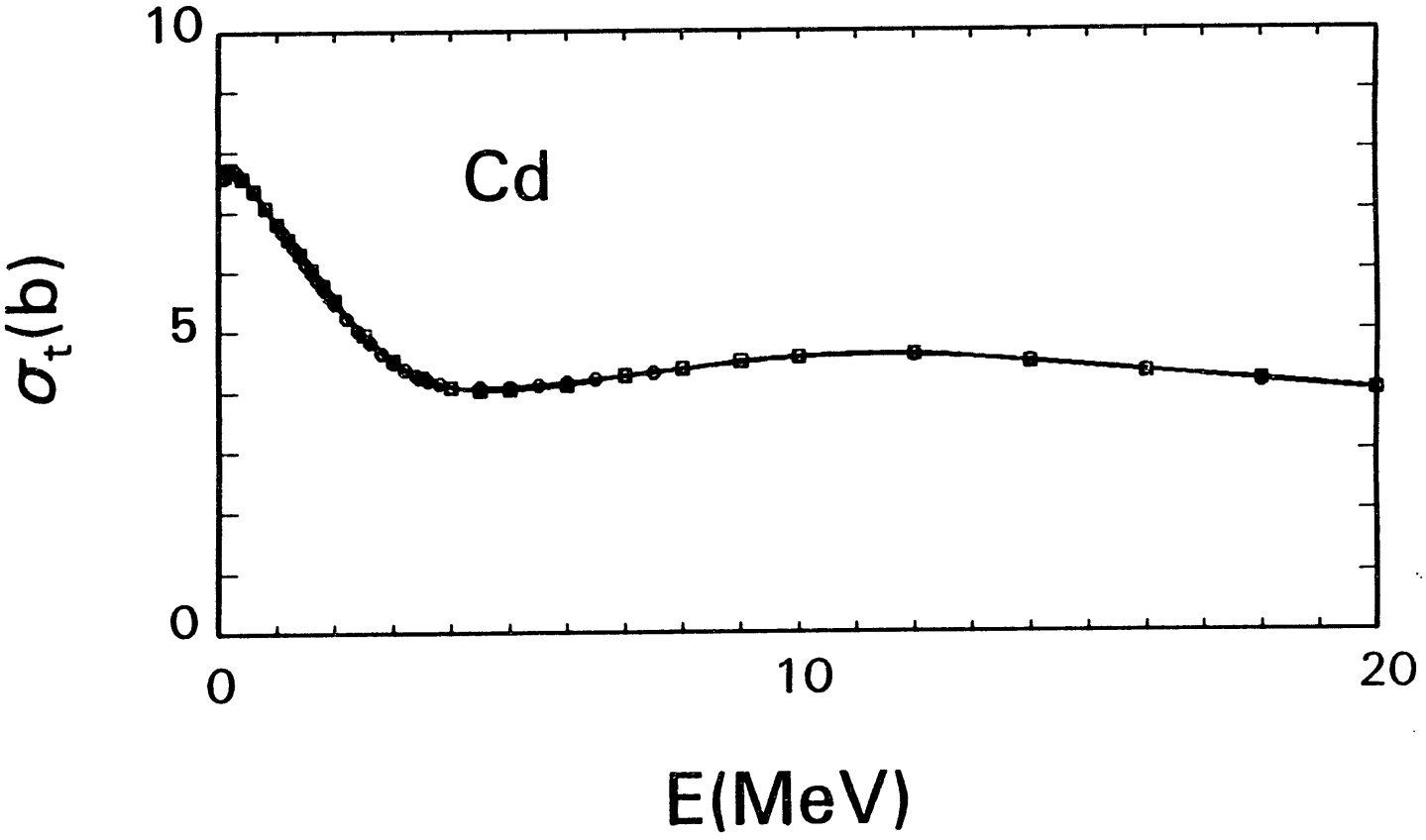

Fig. III-3. Comparisons of the weighted average of the present isotopic total-cross-section evaluations (curve with 0 symbols) and the present elemental evaluation (curve with □ symbols). The two results are indistinguishable.

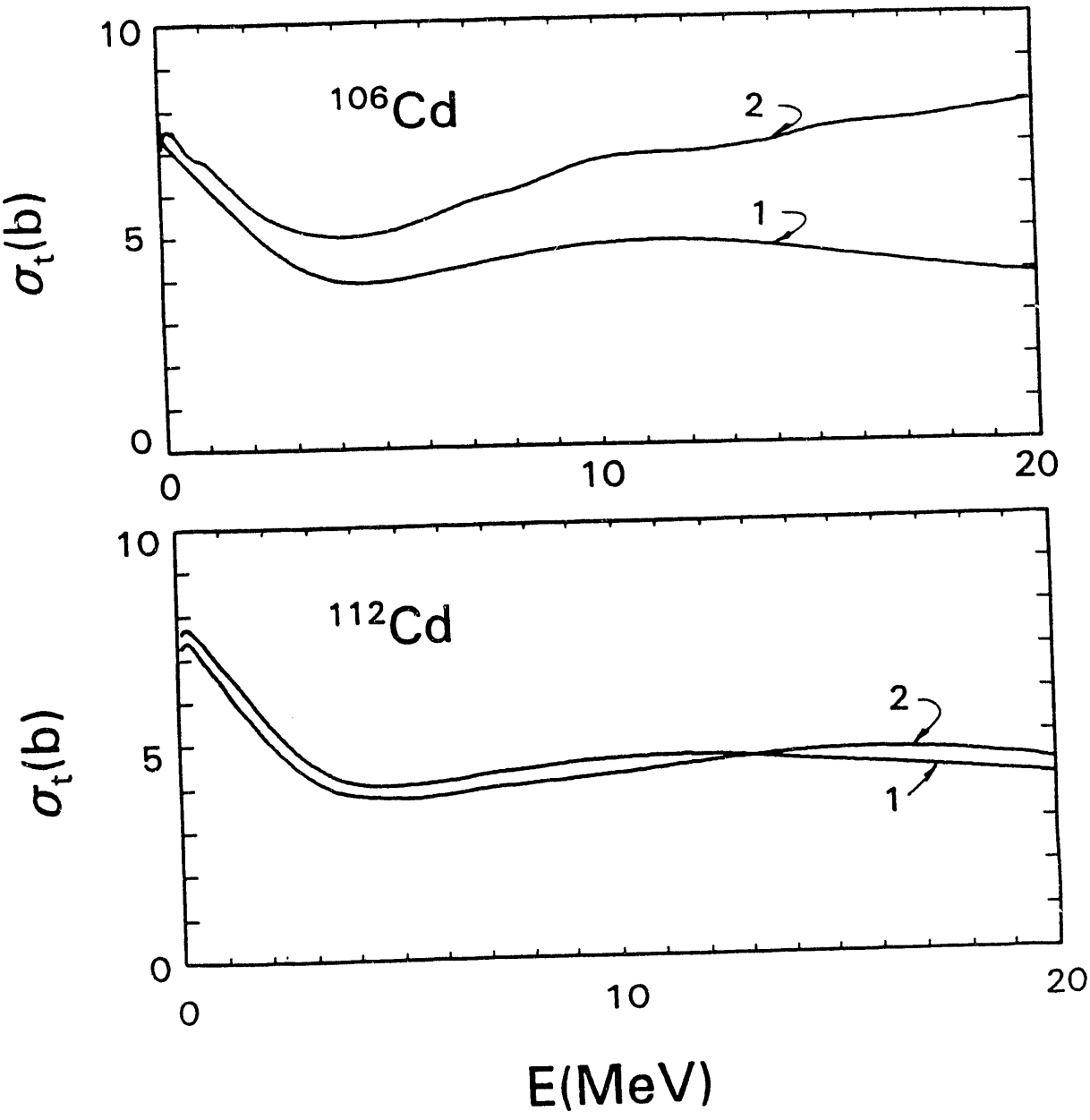

Fig. III-4. Comparison of the present ^{106}Cd and ^{112}Cd total-cross-section evaluations ("1") with those of ENDF/B-VI ("2").

discrepancies are ≈ 5 - 10%, depending on energy. As the present evaluations are internally consistent, this suggests a lack of consistency in the ENDF/B-VI results. These discrepancies also imply that large differences must be present between other aspects of the evaluations (e.g., between elastic- and inelastic-scattering cross sections).

IV ELASTIC-SCATTERING CROSS SECTIONS

The experimental knowledge of neutron elastic scattering from cadmium available at the Data Center [NNDC] is meager, and there is no isotopic information. Above a few-hundred keV the recent experimental results of Smith and Guenther [SG92] give comprehensive new elemental information to ≈ 10 MeV. Above 10 MeV there appears to be no experimental information whatsoever. Therefore, primary reliance was placed upon the elemental work of ref. [SG92], and lower-energy (below 1.5 MeV) work of ref. [VS66]. Ref. [SG92] also includes the detailed optical-statistical model that was used in the present evaluations to interpolate and extrapolate the elastic-scattering from isotope to isotope, and with energy.

-- Recommendation:- High quality elastic-scattering elemental or isotopic measurements are needed at energies above ≈ 10 MeV in order to provide model definition.

At very low energies the present evaluations rely upon the resonance parameterizations outlined in Section II. They are believed to be the best contemporary resonance representations of the cadmium isotopes.

Above the resonance regions, the present evaluations rely upon the model of ref. [SG92] which is soundly based upon elemental elastic-scattering observations to 10 MeV. In extrapolating from the elemental model to the isotopic evaluations, isovector potentials of the forms given in Eq. III-1 were assumed. The exact values of the isovector contributions are not critical as the isotopic dependence is primarily due to the $A^{1/3}$ size dependence of the potential radii. The calculations employed the optical-statistical computer code ABAREX [Mol82], using a Saxon-Woods real potential, a derivative Saxon-Woods imaginary potential, and a Thomas spin-orbit potential [Hod71]. The parameters of these potentials are those given in Table III-1, as taken from ref. [SG92].

Above an incident energy of 12 MeV, it was assumed that the elastic scattering was entirely due to shape-elastic (SE) processes, and the calculations were carried out accordingly. Below an incident

energy of 12 MeV, compound-elastic (CE) scattering contributions were also considered in the calculations. The CE contributions were determined using the Hauser-Feshbach formula [HF52], corrected for resonance width fluctuations and correlations using the method of Moldauer [Mol80]. Discrete excited levels in each of the isotopes were considered where they were reasonably defined by the Nuclear Data Sheets [NDS]. These excited levels are given in Table IV-1. At higher excitation energies, where level specification is uncertain, the calculations used the statistical representation of Gilbert and Cameron [GC65] to determine CN channel competition. The calculations were carried out with a relatively coarse energy mesh, approximately equivalent to that employed in the total cross section evaluation, above.

The calculated elastic-scattering cross sections were adjusted with the same bias factors used in the total cross section evaluations to obtain the evaluated elastic-scattering cross sections. A few of the isotopic elastic-scattering evaluated cross sections are illustrated in Fig. IV-1. There are small systematic differences from isotope to isotope at higher energies. In addition, there are considerable differences at lower energies, where the CN processes are important, due to differing competition with the prominent inelastic-scattering channels. The estimated uncertainties associated with the present elastic-scattering evaluations are of the same order of magnitude as cited above for the total cross sections. Several of the present elastic-scattering evaluations are compared with the respective results given in ENDF/B-VI in Fig. IV-1. There are significant differences depending upon isotope and energy. The worst discrepancy is with ^{106}Cd where the present evaluation differs from that of ENDF/B-VI by more than 300% at some energies. In other cases, the differences are in the order of 5 - 10%, except above $\approx$ 15 MeV where the ENDF/B-VI values are generally 50 - 100% larger. These differences have a strong impact on other aspects of the evaluation. Fig. IV-1 also compares the nonelastic cross sections of the present work with those of ENDF/B-VI. Again, there are large discrepancies. These are particularly significant at lower energies where the present nonelastic cross sections are 50 - 100% larger than given by ENDF/B-VI. The latter difference is primarily reflected in the inelastic-scattering cross section in a region important for fission-product neutronic calculations.

The relative isotopic elastic-scattering angular distributions were determined directly from the above calculations, and expressed in terms of f_1 coefficients. The calculated results, illustrated in Fig. IV-2, are descriptive of the measured values as given in ref. [SG92]. These relative distributions and the elastic-scattering cross sections were tested against the evaluated total cross sections to assure compliance with Wick's Limit [Wic43]. ENDF/B-VI isotopic evaluations represent elastic scattering as isotropic at all energies. That

Table IV-1. Low-lying excitations in the isotopes of elemental cadmium, in MeV [NDS]*.

Isotope:- ^{106}Cd		^{108}Cd		^{110}Cd		^{111}Cd	
E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π
0.000	0^+	0.000	0^+	0.000	0^+	0.000	$\frac{1}{2}^+$
0.633	2^+	0.633	2^+	0.658	2^+	0.245	$\frac{5}{2}^+$
1.494	4^+	1.508	2^+	1.473	0^+	0.345	$\frac{3}{2}^+$
1.717	2^+	1.602	0^+	1.476	2^+	0.396	$\frac{11}{2}^-$
1.795	0^+	1.721	0^+	1.542	4^+	0.417	$\frac{7}{2}^+$
2.105	4^+	1.913	0^+	1.731	0^+	0.620	$\frac{5}{2}^+$
--------		2.146	3^+	1.783	2^+	0.680	$\frac{9}{2}^+$
--------		2.163	2^+	1.809	4^+	0.700	$\frac{7}{2}^+$
--------		2.202	3^-	2.079	0^+	0.753	$\frac{5}{2}^+$
--------		2.239	3^+	2.880	3^-	0.755	$\frac{3}{2}^+$
--------		2.336	2^+	2.163	3^+	0.854	$\frac{7}{2}^+$
--------		--------		2.200	4^+	0.865	$\frac{3}{2}^+$
--------		--------		2.287	2^+	--------	
--------		--------		2.332	0^+	--------	
--------		--------		2.356	2^+	--------	

Table IV-1 continued:-
Isotopes:-

^{112}Cd		^{113}Cd		^{114}Cd		^{116}Cd	
E_x	J^π	E_x	J^π	E_x	J^π	E_x	J^π
0.000	0^+	0.000	$(\frac{1}{2}^+)$	0.000	0^+	0.000	0^+
0.618	2^+	0.264	$(\frac{11}{2}^+)$	0.558	2^+	0.513	2^+
1.224	0^+	0.298	$(\frac{3}{2}^+)$	1.135	0^+	1.213	2^+
1.312	2^+	0.316	$(\frac{5}{2}^+)$	1,210	2^+	1.219	4^+
1.415	4^+	0.458	$(\frac{7}{2}^+)$	1.284	4^+	1.282	0^+
1.433	0^+	0.522	$(\frac{7}{2}^+)$	1.306	0^+	1.381	0^+
1.469	2^+	0.530	$(\frac{7}{2}^+)$	1.364	2^+	1.643	2^+
1.871	0^+	0.584	$(\frac{5}{2}^+)$	1.732	4^+	--------	
2.005	3^-	0.638	$(\frac{9}{2}^+)$	1,842	2^+	--------	
--------		0.681	$(\frac{3}{2}^+)$	1.860	0^+	--------	
--------		0.708	$(\frac{5}{2}^+)$	1.864	2^+	--------	
--------		0.769	$(\frac{1}{2}^+)$	--------		--------	
--------		0.820	$(\frac{7}{2}^+)$	--------		--------	

* In a few cases there are J^π ambiguities. The values used in the calculations are shown in the table.

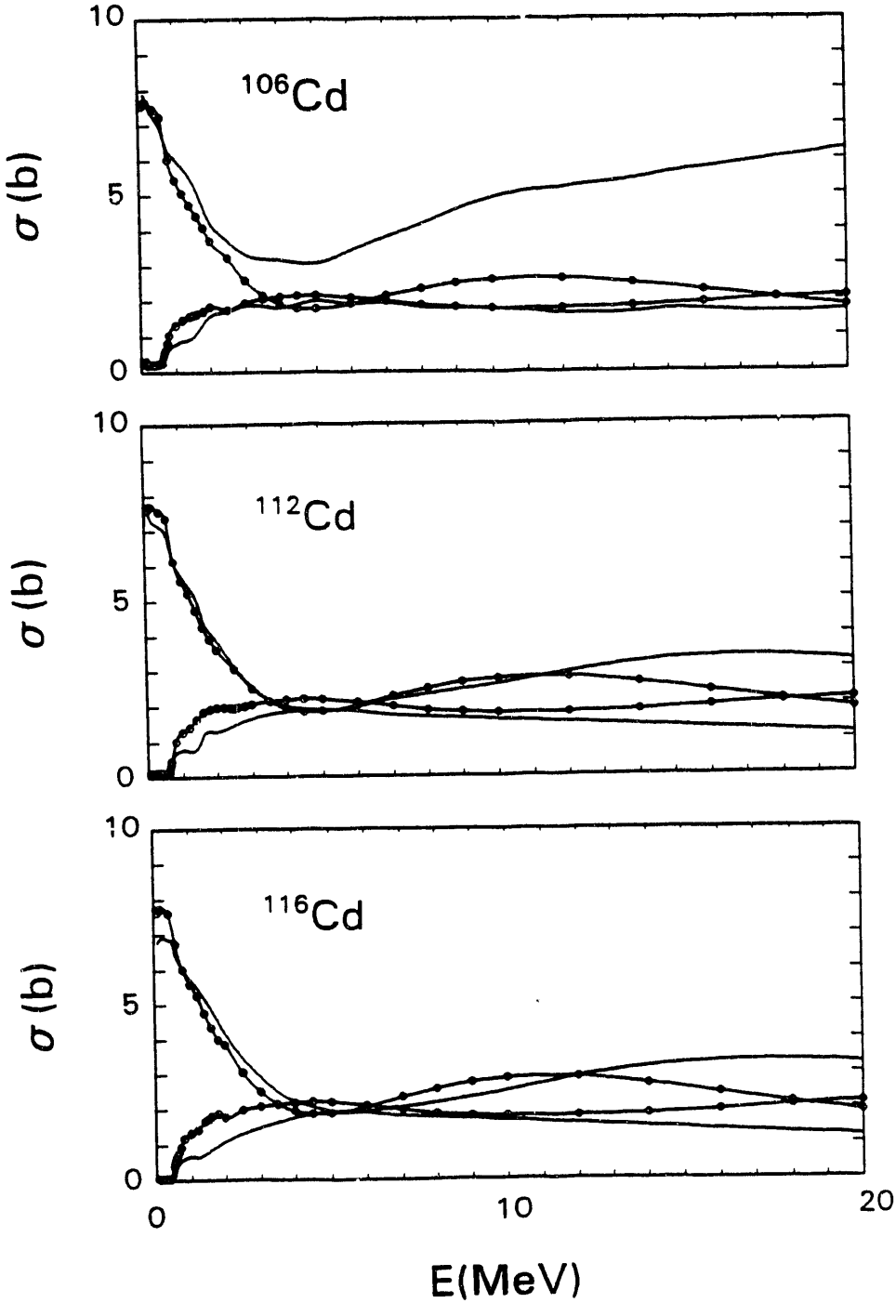

Fig. IV-1. Illustrative comparisons of evaluated isotopic elastic-scattering and nonelastic cross sections of cadmium. The present work is indicated by curves with "O" symbols, and the comparable values from ENDF/B-VI by simple curves.

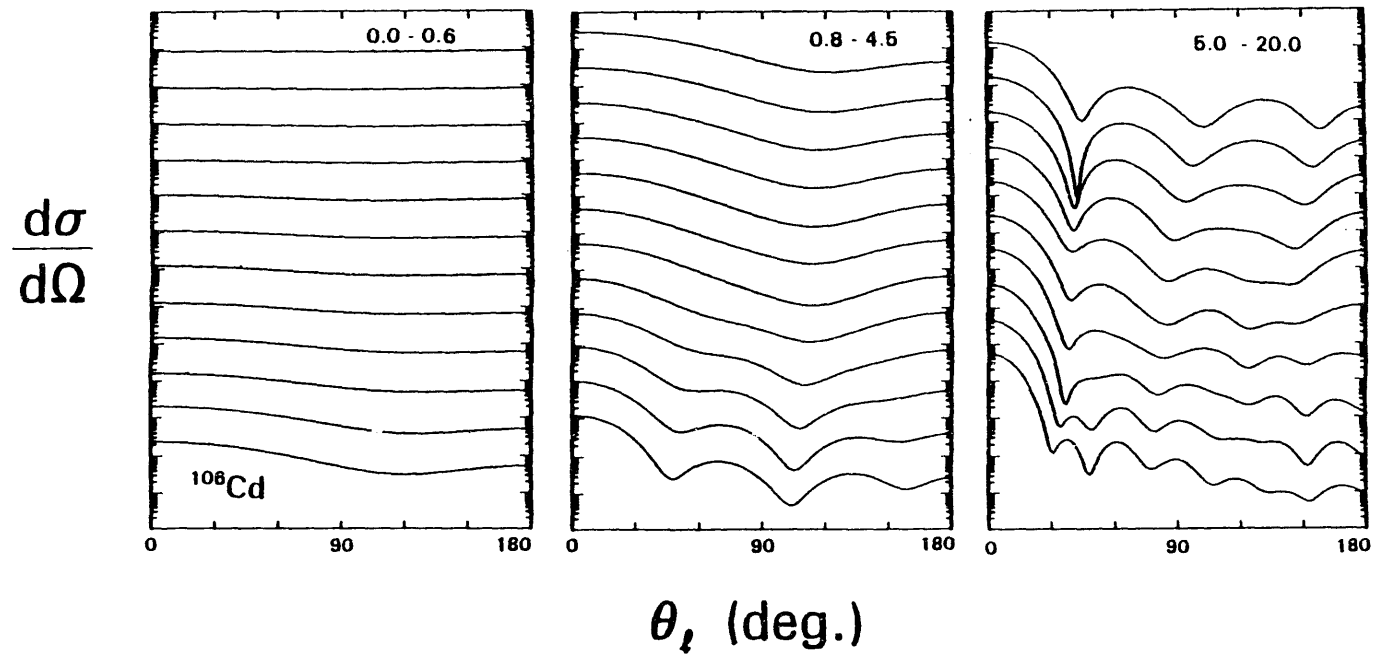

Fig. IV-2. Illustrative relative differential elastic scattering cross sections from the present ^{106}Cd evaluation. The energy ranges of the distributions (top to bottom, in MeV) are numerically indicated in each section of the figure.

representation is grossly invalid at all but the very lowest energies. The anisotropy approaches an order of magnitude at only 0.6 MeV, and is several orders of magnitude at higher energies. The assumption of isotropy of elastic scattering at all energies has the potential for serious applied consequences.

V. INELASTIC SCATTERING

A. Discrete Excitations

Discrete inelastic-scattering excitations are given for the levels defined in Table IV-1. The excitation cross sections were calculated using the model described above, and discussed in detail in ref. [SG92]. It is shown in that reference that this particular model gives a good representation of the experimentally-determined inelastic-scattering values. The calculations primarily considered compound-nucleus contributions (CN), and they are the major part of the cross sections where they are of appreciable size. However, the cadmium isotopes display characteristics of collective vibrators [SG92]. As a consequence there is a small direct inelastic-scattering component (DR) to be added to the major CN contribution. At low energies (e.g., several MeV) the DR inelastic-scattering contribution is relatively small. However, above ≈ 10 MeV it is by far the largest constituent of the discrete inelastic-scattering cross sections. The DR contribution was calculated assuming a one-phonon vibrational model using the coupled-channels code ANLECIS [Mol81]. β_2 was taken to be 0.168, following the work of ref. [SG92]. In that reference it is shown that DR coupled-channels calculations reasonably represent the observed inelastic-scattering cross sections at higher energies. The DR model is most appropriate for the even isotopes. It was extended to the odd isotopes assuming that the one-phonon DR strength was shared by the $J = 2 \pm 1/2$ yrast levels. The relative DR contributions to these pairs of levels was weighted by the statistical factor $2 \cdot J + 1$. It was further assumed that there was no correlation between CN and DR inelastic contributions; i.e., the CN contribution was calculated with the spherical-model transmission coefficients rather than those of the deformed potential. For most applications these approximations do not significantly compromise the result as the DR contribution is small at energies of primary applied interest. The discrete inelastic-scattering cross sections obtained in the above manner are large, particularly for the yrast 2^+ levels where they range from ≈ 1.2 → 2.0 b at relatively low energies. Illustrative discrete-inelastic scattering results are shown in Fig. V-1. There are small artifacts in these illustrated distributions near the thresholds due to the relatively coarse energy mesh used in the evaluations. They can be avoided by increasing the energy-detail of the evaluations, but at the expense of considerably increasing the size of the files. These artifacts will have negligible effect in the

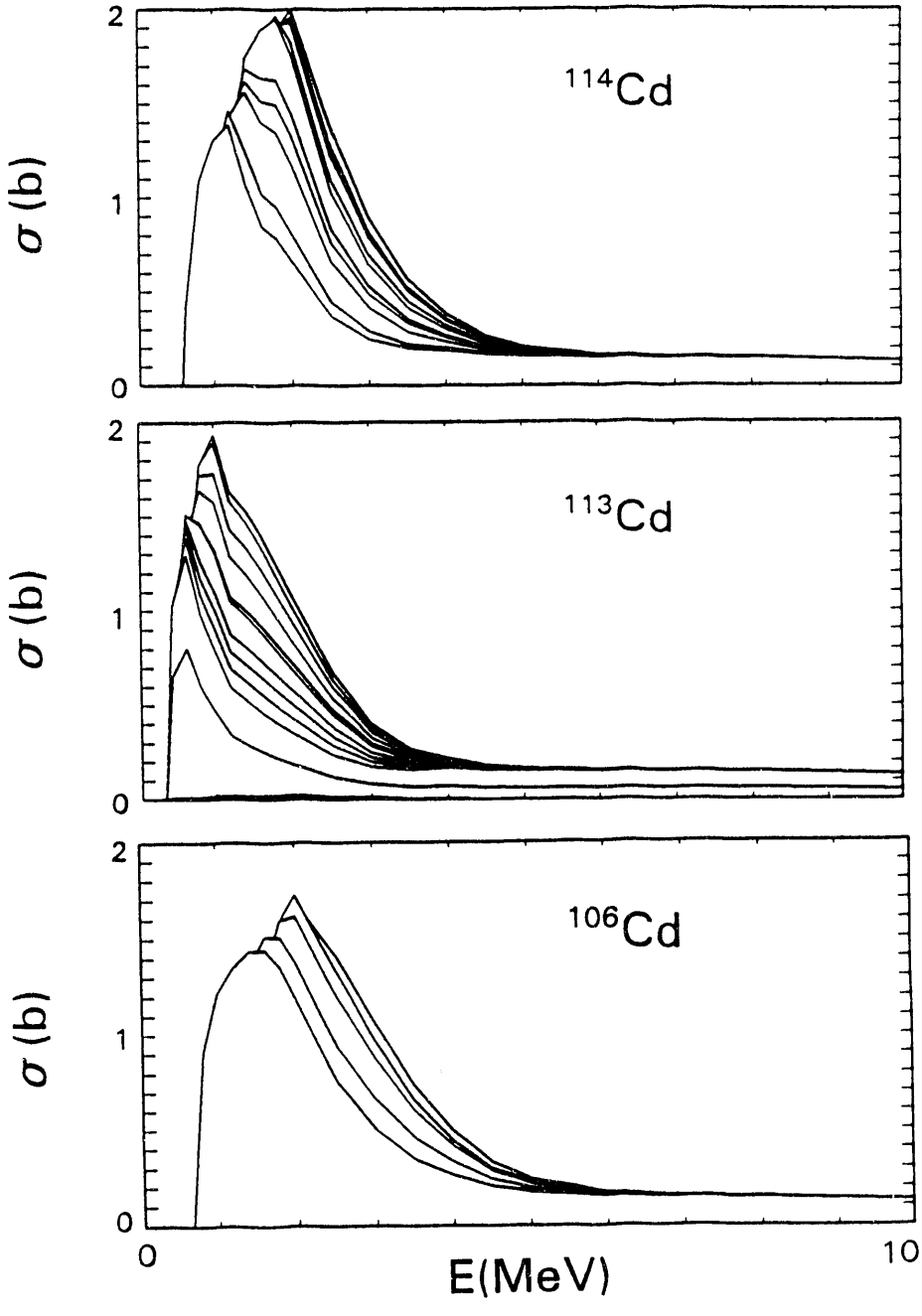

Fig. V-1. Illustrative cumulative discrete-inelastic-excitation cross sections of ^{106}Cd, ^{113}Cd and ^{114}Cd whereby the cross sections for successive levels are added together. The curves follow from the present evaluations.

typical energy-group application of the files, thus the additional extensive detail was sacrificed for practical conciseness.

The discrete inelastic-scattering cross sections of the present evaluations are remarkably different from those given in ENDF/B-VI at the important lower energies (e.g., at ≈ 1.0 MeV the present evaluations are approximately a factor of two larger than given in ENDF/B-VI). These differences are the primary contribution to the nonelastic-scattering discrepancies cited in Section IV. They should be a concern in FBR fuel cycle and fission-product considerations. There are uncertainties associated with all of the evaluated inelastic-scattering data. In the present case they are estimated to be ≈ 10% in regions of prominent cross sections, and that estimate is supported by ref. [SG92]. The uncertainties in the present evaluations, in regions of large cross section, are small relative to the discrepancies with ENDF/B-VI.

In regions of large magnitude, the discrete inelastic-scattering cross sections are primarily due to CN processes. As a consequence, the inelastically-scattered neutrons are emitted essentially symmetrically about 90^0, and the calculated angular distributions approach isotropy. Thus the present evaluations assume the isotropy of the emitted discrete inelastically-scattered neutrons. This approximation breaks down at higher energies (e.g., ≥ 10 MeV) where the discrete inelastic-scattering is essentially entirely due to DR processes. The latter lead to inelastic neutron emission that is strongly peaked forward. For simplicity this effect was ignored in the present evaluations, and the consequences will be negligible in most applications as the corresponding cross sections are quite small. The assumption of inelastic-scattering isotropy is also inherent in ENDF/B-VI, when discrete excitations are given at all.

B. Continuum Excitations

There is very little experimental information dealing with continuum inelastic scattering from the cadmium isotopes. Thus, in the present evaluations the magnitudes of the continuum inelastic-scattering cross sections were determined by the difference between the total non-elastic cross sections and the sum of the other partial non-elastic cross sections. The consequences are continuum inelastic-scattering cross sections that rise from the upper limit of the discrete-excitation thresholds to relatively large magnitudes, and persist at these large values until the onset of the (n,2n) cross sections. At that point they fall toward relatively small values which are largely due to pre-compound contributions. This behavior is illustrated in Fig. V-2. The present continuum inelastic-scattering cross sections are considerably different from those outlined in ENDF/B-VI (by as much as 300+% at higher energies), as they must be

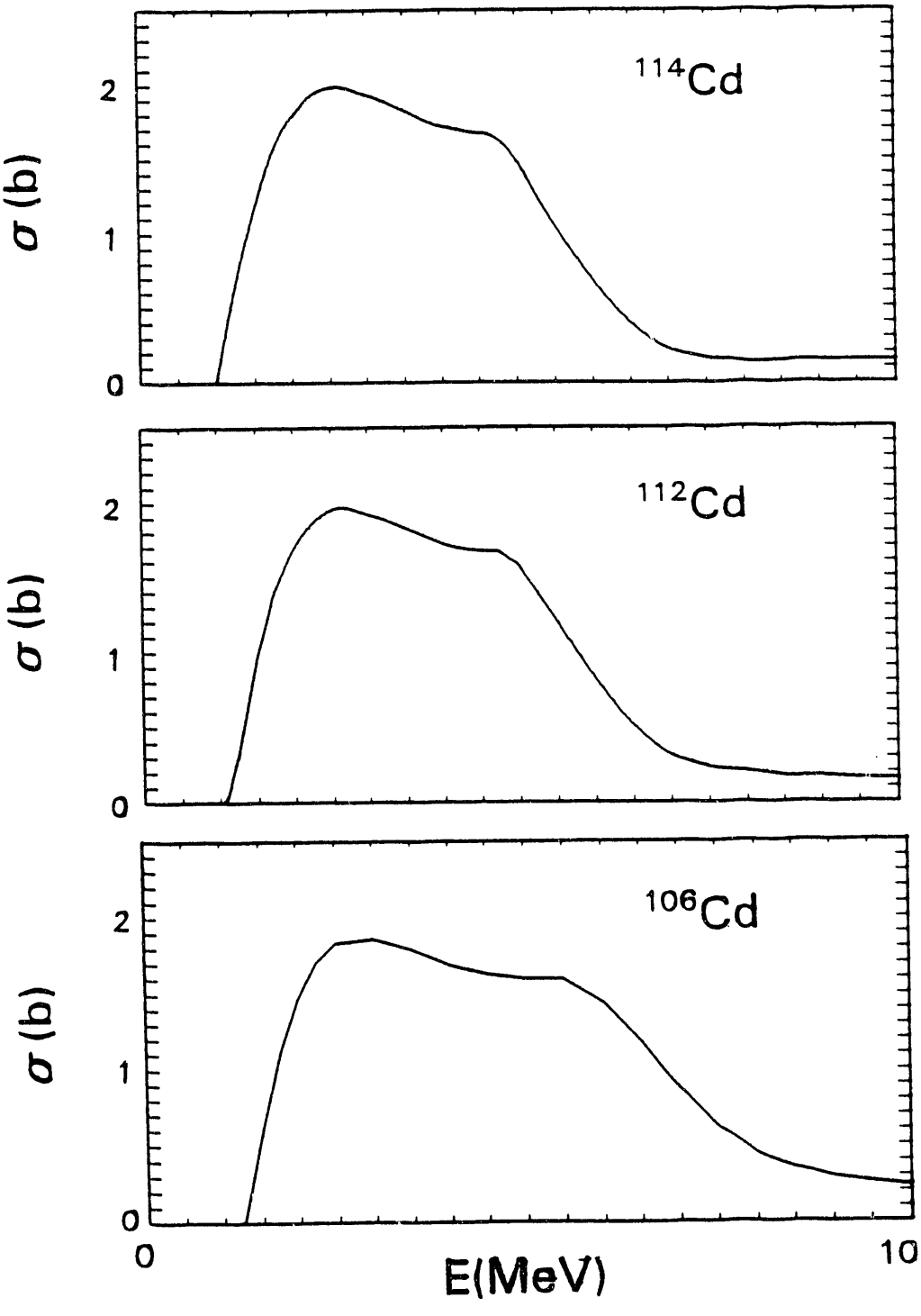

Fig. V-2. Illustrative evaluated continuum inelastic-scattering cross sections of ^{106}Cd, ^{112}Cd and ^{114}Cd. The curves follow from the present evaluations.

since the ENDF/B-VI evaluations are devoid of the large competing (n,2n) contributions.

At lower energies the continuum inelastic scattering is primarily a CN process, and the neutron emission approaches isotropy. For this reason, isotropy was assumed in the present continuum evaluations. The approximation is less suitable at higher energies where pre-compound emission becomes substantive, with the consequence of considerable anisotropy in the neutron emission. The latter effect was ignored as it introduces considerable complexity in the evaluations, depends on model judgments, and will have little effect on most applications. ENDF/B-VI also specifies isotropy of continuum neutron emission.

The continuum inelastic-scattering emission spectra consist of CN and pre-compound components. In the present evaluations, the CN component of the spectra was represented by a simple Weisskopf distribution [BW52], with the temperature following a $(E/a)^{1/2}$ energy dependence, where E is the incident energy and "a" the level density parameter. To the CN component was added a pre-compound contribution which was again a Weisskopf distribution but with the temperature 3.5 times that of the CN component, following the procedure of Frehaut [Fre76]. The relative intensity of the pre-compound component was assumed to be ≈ 2.5%. These spectral assumptions are no more than qualitative, but they are simple, physically reasonable, and introduce the concept of pre-compound emission not present in the ENDF/B-VI evaluations. Most applications involve neutron energies well below those of significant pre-compound contributions.

-- Recommendation:- The double differential neutron emission spectrum of elemental cadmium should be measured at several incident energies in the 10 → 20 MeV interval.

VI. RADIATIVE CAPTURE

The resonance-capture processes are inherent in the resonance-parameter representations of Section II, above. At higher energies, there is very little experimental knowledge of the energy-averaged radiative capture cross sections of the isotopes of elemental cadmium. The reported measured values are very largely confined to the work of Musgrove et al. [Mus+82]. Those authors provide detailed experimental information from ≈ 3 keV to several hundred-keV for all the naturally-occurring isotopes of cadmium excepting ^{116}Cd. The measurements were made using the white-source technique with Moxon-Rae detectors. With this sparse experimental data base, the present evaluations relied upon the model of Smith and Guenther [SG92], and the computer code ABAREX [Mol82] to calculate the

energy-dependent shape of the capture cross sections, normalizing the magnitudes to the experimental values of Musgrove et al. by adjusting the γ strength functions. The calculations are based upon the Brink-Axel formalism [Axe63], and use systematic expressions for the position and width of the giant dipole resonance [Law92]. In addition, the neutron binding energy was taken from the Wallet Cards [WAL90]. The calculations employed the potential parameters of Table III-1, and gave attention to channel competition using the excited level structures defined in Table IV-1. The calculations were confined to compound-nucleus processes. Direct capture processes were assumed to be small and ignored.

The energy-averaged capture cross sections obtained in the above manner extend from the upper energy limit of the resonance parameterization at $\approx 5 \rightarrow 100$ keV to 20 MeV. For the even isotopes there is a smooth A-dependence of the γ-ray strength following from the above calculations and the adjustment to the experimental results. This suggests that the experimental results and calculations are isotopically consistent. The yrast-level inelastic-scattering cross sections of the even isotopes are large with the consequence of strong channel competition and resulting cusps in the capture cross sections near the threshold for the inelastic excitations of, particularly, the yrast 2^+ levels. The two odd isotopes are more difficult. There is experimental information for only one, ^{111}Cd, and the capture cross sections of the other, ^{113}Cd, must be estimated entirely from the model and the systematic behavior of the γ-ray strength. The odd-isotope capture cross sections are larger, primarily as a consequence of the much reduced average level spacing compared with that of the even isotopes.

The elemental capture cross sections were constructed from the isotopic components using a weighted sum of isoptopic components. This result can be compared with some available elemental cadmium capture cross sections ([Gib+63], [Mac+63], [DTH60], [Blo+61], [Poe82] and [Kom69]), though such a comparison is not sensitive to the low-abundance contributions. The elemental comparisons are encouraging as the elemental results constructed from the present isotopic evaluations are within 5 - 15% of the measured values from a few keV to a few MeV. In the few-hundred keV region the evaluation tends to be somewhat larger than the measured values, and conversely in the few keV region.

Agreement with the isotopic evaluations of ENDF/B-VI varies widely :- for ^{106}Cd very poor, for ^{108}Cd poor, for ^{110}Cd fair, for ^{111}Cd poor, for ^{112}Cd good, for ^{113}Cd fair, for ^{114}Cd very poor, and for ^{116}Cd fair (in the worst cases the discrepancies are $\approx$ a factor of two). These variations suggest a considerable lack of isotopic consistency in the ENDF/B-VI evaluations. Recently, Wright has

reported new capture evaluations for the even cadmium isotopes [Wri93]. His results are generally in acceptable agreement with the present work, excepting only the regions where there is very strong competition from the inelastic channels. In these regions the present evaluations show more-prominent cusps than the evaluations of ref. [Wri93]. Illustrative comparisons of the present evaluations and those of ref. [Wri93] and ENDF/B-VI are shown in Fig. VI-1.

The uncertainties of the present energy-averaged capture evaluations of the even isotopes of cadmium are estimated to be $\lesssim$ 15% in regions of appreciable cross section. The uncertainty is perhaps a bit larger for the two odd isotopes as the experimental foundation is so weak. These uncertainty estimates are supported by the measurements of Musgrove et al [Mus+82] and the even-isotope evaluations of Wright [Wri93].

The above evaluations are greatly dependent upon a single set of isotopic capture measurements [Mus+82]. That is a very limited foundation. Therefore;

-- Recommendation:- Energy-averaged isotopic capture measurements should be made from a few keV to above 1 MeV to accuracies of $\lesssim$ 10%.

Such measurements are difficult but feasible-- providing isotopic samples are available.

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

The isotopic thresholds for the (n,2n) reactions are at $\approx$ 9 - 11 MeV, as given in Table VII-1. The thresholds for the (n,3n) reactions are in the range $\approx$ 15 - 20 MeV. The ^{106}Cd (n,3n) threshold is so near 20 MeV that the reaction was ignored in the present evaluation.

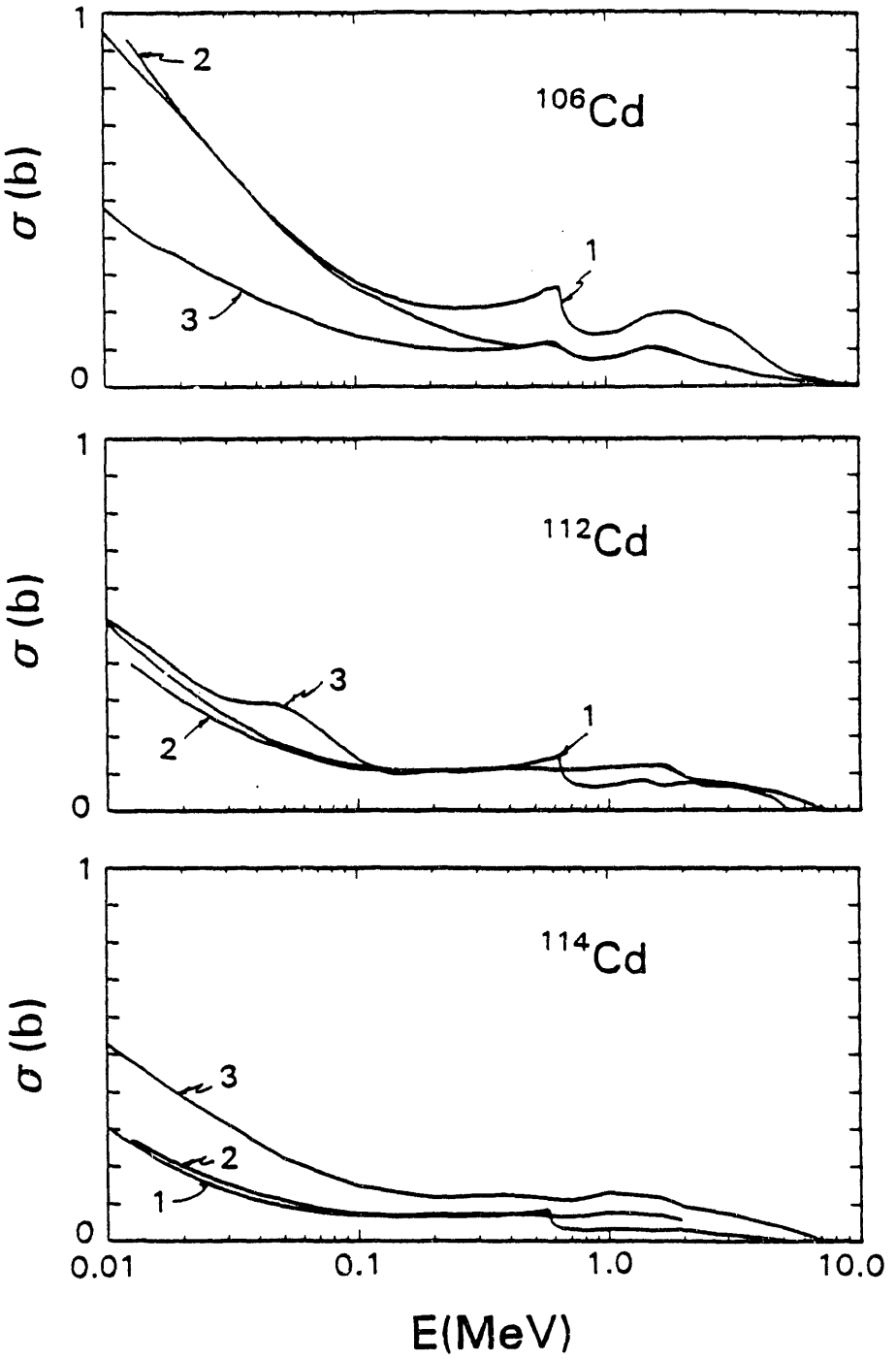

Fig. VI-1. Illustrative comparisons of the present capture cross-section evaluations ("1") with those of ref. [Wri93] ("2") and ENDF/B-VI ("3").

Table VII-1. (n,2n) and (n,3n) thresholds of the cadmium isotopes (in MeV).*

Isotope	(n,2n)	(n,3n)
106	10.969	19.609
108	10.431	18.434
110	9.971	17.399
111	7.039	17.010
112	9.481	16.520
113	6.602	16.082
114	9.120	15.722
116	8.772	14.971

* Taken from Lawrence Livermore National Laboratory Tables [How93].

The experimental knowledge of the (n,2n) and (n,3n) processes is very limited as the extended string of isotopes precludes conventional activation measurements in most cases. Predictably, the extreme ends of the isotopic chain (^{106}Cd and ^{116}Cd) have received the most attention, but in even those cases the experimental information is only fragmentary. The activation (n,2n) measurements are confined to ref. [Ray61], [Ray63], [LF69], [Bor+68], [WMH75], [KH74], [YG67], [Gon+87], [LRF70], [KH61], [KNK79] and [PB61]. In addition, there have been some activation measurements of metastable-state excitations that, obviously, do not directly give the total (n,2n) cross sections. Oddly, there has been only one prompt neutron-detection scintillation-tank measurement, and that is for the element and at the isolated energy of ≈ 14.1 MeV [ACN58].

-- Recommendation:- (n,2n) and (n,3n) cross sections of elemental cadmium (and isotopes if available) should be measured over the ≈ 10 - 20 MeV energy range using prompt-detection (scintillation-tank) techniques.

Such measurements are technologically feasible, and would provide a valued normalization and energy dependence of the two cross sections. While the experimental knowledge of the (n,2n) cross sections is no better than fragmentary, that of the (n,3n) cross sections is apparently non-existent.

With the above unfortunate experimental situation, the present evaluations relied upon GNASH calculations [YAC92]. The necessary neutron potential was taken from ref. [SG92], the proton, deuteron,

triton and ^{3}He potentials from ref. [PP76], and the alpha potential from ref. [Fer91]. The calculated cross sections were compared with the fragmentary ^{106}Cd and ^{116}Cd experimental values with the results shown in Fig. VII-1. The experimental data is discrepant, but the calculated results seem to be reasonably consistent with a number of the measured values near 14 MeV. The calculated shapes towards thresholds are largely governed by transmission coefficients and should be reasonably represented. Above ≈ 14 MeV the situation is difficult due to the lack off, or discrepancy between, experimental data. In view of these large uncertainties, the calculated (n,2n) and (n,3n) cross sections were accepted for the evaluations without adjustment. Quantitative tests of the calculated results will require far better experimental information.

The emitted-neutron spectra were approximated by a simple Weisskopf evaporation spectrum, with a temperature given by $\theta = (E/a)^{1/2}$, where "a" is the cadmium level-density parameter [BW52]. This is a qualitative approximation, but, in view of the uncertainties in the evaluation, more detailed representations are probably not warranted. With this simple model, the emitted neutrons are isotropically distributed.

The estimated uncertainties associated with the present (n,2n) and (n,3n) evaluation are probably quite large, perhaps 10 - 20% or more. However, this is certainly an outstanding improvement over ENDF/B-VI isotopic cadmium evaluations which are completely devoid of (n,2n) and (n,3n) reactions. At higher energies, the impact of this shortfall is acute as it implies inelastic-scattering errors of factors of 2 → 4, as outlined in Section V.

VIII. (n,X) REACTIONS

There are a number of energetically available (n,X) reactions in the cadmium isotopes, as outlined in Table VIII-1. Many of the respective cross sections are very small, and experimental information is sparse. The present evaluations must place primary reliance on the results of calculations, subjectively adjusted to agree with the measured data when the latter are available. The resulting evaluations are little more than qualitative, but the (n,X) reactions are included for qualitative guidance and completeness. The shortfall in the evaluated (n,X) reactions will have little effect in most applications due to the small magnitudes of the cross sections and the relatively high energies of the respective thresholds.

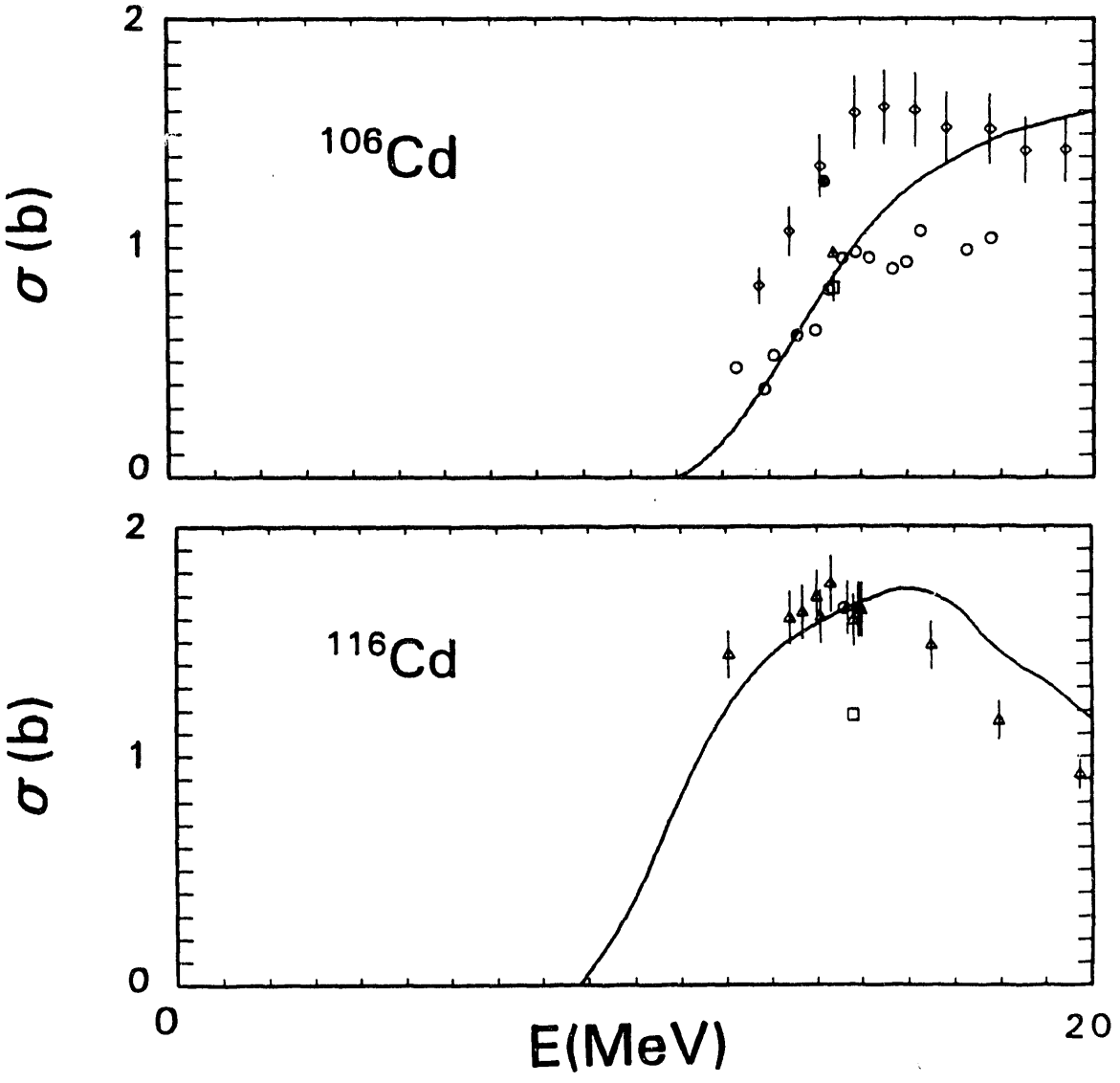

Fig. VII-1. Comparisons of evaluated (curves) and measured (symbols) (n,2n) cross sections of ^{106}Cd and ^{116}Cd.

Table VIII-1. (n,X) Reaction Thresholds in MeV.*

A	(n,p)	(n;n,p)	(n,α)	(n;n,α)	(n,d)	(n;n,d)
106	-0.580	7.415	-5.994	1.646	5.169	15.260
108	0.874	8.212	-4.818	2.297	5.967	15.603
110	2.130	8.998	-3.668	2.887	6.753	16.029
111	0.247	9.169	-5.916	3.338	6.925	13.792
112	3.204	9.728	-2.674	3.511	7.483	16.405
113	1.239	9.806	-4.931	3.904	7.562	14.085
114	4.113	10.359	-1.657	4.145	8.115	16.682
116	5.362	11.194	-0.568	4.859	8.950	16.840

A	(n,t)	(n;n,t)	(n,^{3}He)	(n;n,^{3}He)
106	8.944	17.446	4.635	14.723
108	9.287	17.287	6.256	15.908
110	9.714	17.051	7.757	17.066
111	7.478	16.753	8.586	14.796
112	10.092	16.959	9.186	18.066
113	7.772	16.693	9.970	15.787
114	10.369	16.892	10.647	19.089
116	10.528	16.773	11.330	20.185

* Taken from the Lawrence Livermore National Laboratory tables [How93].

A. The (n,p) Processes

There is scattered experimental information on the (n,p) reaction in the various cadmium isotopes ([LF70], [MRK74], [Bor+68], [WMH75], [Lev63]. [SW74], [KNK79], [PAB85], [PS66], [PB61], [YG67], [LRF70], [CPB77], [Her+78], [BA73] and [Ste67]). In addition, there are some scattered results from measurements of metastable excitations. Most of the experimental data is centered about ≈ 14 MeV, with little knowledge of the energy-dependent shape, and for one isotope (^{108}Cd) there is apparently no experimental information. In view of this weak experimental data base, considerable reliance was placed upon the GNASH calculations [YAC92], following the procedures outlined in Section VII. The energy dependencies of these calculated results were used throughout the evaluations. Where significant experimental data were available, the calculated results were subjectively normalized to the experimental results at ≈ 14 MeV. The normalization factor for ^{106}Cd was 1.65, for ^{110}Cd 1.33, for ^{111}Cd 2.40, for ^{112}Cd 2.60 and for ^{113}Cd 1.10. For the other isotopes the calculations were used without normalization as the agreement with the measured values was very good or none of the latter were available. Some of these normalization factors are quite large, and they probably reflect uncertainties in both the calculations and the reference experimental values. A qualitative uncertainty guideline is >≈ 25% at 14 MeV, with probably larger uncertainties at higher energies. These are significant uncertainties but the evaluated (n,p) cross sections never exceed 100 mb at the highest energies, and generally are very much smaller. Predictably, the largest cross sections are for the lighter isotopes, as one would expect from a qualitative tendency to return to the line of β-stability by proton emission.

The ENDF/B-VI isotopic cadmium files contain no (n,p) reactions for comparison. The quite different elemental cadmium ENDF/B-VI file (MAT4800) gives a 14 MeV (n,p) cross section value that differs from the elemental value constructed from the present isotopic evaluations by only ≈ 15%. This is reasonable agreement considering the various uncertainties involved.

Most of the isotopic cadmium (n,p) cross sections can be simply determined with activation techniques at a monoenergetic source facility. Therefore:-

-- Recommendation:- Activation measurements of the (n,p) cadmium isotopic cross sections should be systematically studied from threshold to 20 MeV.

It is doubtful that the present (n,p) evaluations can be significantly improved until such experimental information becomes available.

B. The (n,α) Processes

The (n,α) cross sections were calculated with GNASH as outlined in Section VII. The calculated values are all small, the largest being the ^{106}Cd cross sections which reached a magnitude of $\approx$ 25 mb at 20 MeV. The cross section magnitudes fall rapidly with mass to values of $\lesssim$ 1 mb for ^{116}Cd. The experimental information available for testing the calculated results is very fragmentary. There is a single measurement of the (n,α) cross section of ^{106}Cd near 14 MeV [YG67]. The result is a factor of approximately four larger than the calculations, and an order of magnitude larger than the experimental values from any other cadmium (n,α) measurements. There appear to be no experimental (n,α) cross-sections for ^{108}Cd, ^{110}Cd, ^{111}Cd and ^{113}Cd. There are four measurements of the (n,α) reaction in ^{112}Cd, largely centered about 14 MeV ([YG67], [Lev63], [BP61] and [DLM56]). Two of these data sets agree with the calculations, and the other two are approximately a factor of two larger. There are two $\approx$ 14 MeV measurements of the ^{114}Cd (n,α) cross section, both of which are at $\approx$ 14 MeV and reasonably consistent with the calculated results ([YG67], [Lev63]). There is a single measurement of the ^{116}Cd (n,α) cross section near 14 MeV [YG67]. The experimental result is larger than the calculated value, but both are a small part of a mb. In view of the above situation, the evaluations were based upon the calculated results. The uncertainties may be rather large (e.g., 50 - 100%), but the cross sections are generally very small and thus will be of little concern in neutronic applications. The improvement of the (n,α) evaluations will probably require significantly better measurements that give a good benchmark for testing the calculations. Therefore:-

-- Recommendation:- (n,α) cross sections of the cadmium isotopes should be measured over a wide energy range to accuracies of 10 - 20%.

In a number of the cases simple activation techniques should give suitable results.

ENDF/B-VI contains no (n,α) results for comparison.

C. The (n,d) Processes

The experimental evidence for this reaction appears to be confined to one activation measurement [LF69] which can not differentiate between the (n,d) and (n;n,p) processes. Therefore the evaluation relies entirely on the calculational estimates of GNASH. The results may have a large uncertainty, but the calculated cross sections are small, of the order of 10 mb at 20 MeV and much smaller

at lower energies. There are no comparable cross sections in the ENDF/B-VI evaluated files.

D. The (n,t) Processes

There appears to be only one experimental value [WS78] which gives a cross section of the order of 20 μb at $\approx$ 14 MeV. GNASH calculations give similar very small cross sections. They are included in the file for completeness though they may be in error by as much as an order of magnitude. This large uncertainty is of no concern in the vast majority of applications as the cross sections are so small. The ENDF/B-VI files contain no comparable information.

E. The (n,^{3}He) Processes

There seems to be no experimental information dealing with this reaction. The GNASH calculations indicate cross sections in the μb range over most of the energies of the evaluations. The calculated results are included in the evaluations for completeness, but the uncertainties may be large. There is no comparable information in the ENDF/B-VI isotopic files.

F. The (n;n,p) Processes

As noted above, the single relevant activation measurement can not distinguish between the (n;n,p) and (n,d) processes. The calculated results are typically in the order of ten mb at 20 MeV, and less then a mb at 14 MeV. The values are larger for ^{106}Cd. The evaluations use the calculated results, but there may be considerable uncertainties in the values. The neutron emission is assumed to be isotropic, and the spectra are represented with simple Weisskopf temperature distributions. These are qualitative approximations, but of little neutronic importance due to the small cross section magnitudes. The ENDF/B-VI isotopic files contain no comparable information.

G. The (n;n,α) Processes

These processes were treated in the evaluations in a manner analogous to that outlined above for the (n;n,p) reactions. The cross sections are even smaller than those of the (n;n,p) processes. Again, there is no relevant information in the ENDF/B-VI isotopic files.

H. The (n;n,d) Processes

The thresholds of these reactions are above ≈ 15 MeV. GNASH calculations give cross sections that are of the order of a few μb or less, generally much less. There may be considerable uncertainty in these calculated values, but clearly the cross sections are very small. In view of the high thresholds and small cross-section values, these cross sections are of essentially no applied neutronic interest. They were included in the evaluations only for qualitative guidance and completeness, using the same calculational approach outlined above for the (n;n,p) processes.

I. The (n;n,t) Processes

These cross sections are still smaller than the those of the (n;n,d) processes. They were treated in an identical manner, and included in the evaluation only for qualitative guidance and completeness.

J. The (n;n,^{3}He) Processes

These processes are calculated to be even smaller than the (n;n,t) reactions cited above, and the thresholds are quite high. Thus they were omitted in the present neutronic evaluations.

There is some experimental evidence that a few of the above (n,X) reactions lead to measurable cross sections at very low energies. These possible thermal, or epi-thermal, (n,X) cross sections are not addressed in the present evaluations.

IX. SUMMARY AND RECOMMENDATIONS

There are gross differences between the present evaluations and the comparable isotopic evaluations of ENDF/B-VI. These differences are in magnitudes of prominent cross sections and in scope. They are far beyond any reasonable uncertainty estimates, and have the potential for pronounced impacts on neutronic applications. The present evaluations were undertaken in a horizontal manner that resulted in good consistency, in contrast to the comparable ENDF/B-VI evaluations. In a number of areas the present files remain inherently uncertain due to the shortcomings in the experimental foundation. Very probably, these uncertainties will be resolved only when relevant experimental information, of good quality, becomes available. In

particular, the following measurement regimes are recommended:-

1. Comprehensive high-resolution resonance measurements of the isotopes of cadmium should be undertaken, assuring complete energy coverage to at least 10 keV.

2. Energy-averaged, or partially resolved, total cross section measurements should be made from a few keV to 100+ keV.

3. High quality elastic-scattering elemental or isotopic measurements are needed at energies above ≈ 10 MeV in order to provide model definition.

4. The double differential neutron-emission spectrum of elemental cadmium should be measured at several incident energies in the 10 → 20 MeV interval.

5. Energy-averaged isotopic capture measurements should be made from a few-keV to above 1 MeV to accuracies of <≈ 10%.

6. (n,2n) and (n,3n) cross sections of elemental cadmium (and isotopes if available) should be measured over the 10 - 20 MeV energy range using prompt-detection (scintillation tank) techniques.

7. Activation measurements of the (n,p) cadmium isotopic cross sections should be systematically studied from thresholds to 20 MeV.

8. (n,α) cross sections of the cadmium isotopes should be measured over a wide energy range to accuracies of 10 - 20%.

These measurement recommendations are consistent with present technological capability.

The numerical files resulting from the present work are extensive, cumulatively amounting to ≈ 10000 lines. They have been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. Interested users can obtain these isotopic cadmium evaluations from that institution, or by contacting the authors.

REFERENCES

ACN58 V. J. Ashby, H. C. Catron and L. Newkirk, Phys. Rev. 111 616 (1958).

Axe63 P. Axel, K. Min, N. Stein and D. C. Sutton, Phys. Rev. Lett. 10 299 (1963).

BA73 T. Bjornstad and J. Alstad, Phys. Rev. Lett. 14 247 (1973).

Blo+61 R. C. Block et al., Proc. Saclay Nucl. Data Conf. (1961).

Bor+68 M. Borman et al., Nucl. Phys. A115 309 (1968).

Bow+61 P. Bowen et al., Nucl. Phys. 22 640 (1961).

BP61 B. P. Bayhurst and R. J. Prestwood, J. Inorgan. Nucl. Chem. 23 173 (1961).

BPS58 A. Bratenahl, J. Peterson and J. Stoering, Phys. Rev. 110 927 (1958).

BW52 J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley and Sons, New York, 1952).

CGB52 J. Coon, E. Graves and H. Barschall, Phys. Rev. 88 562 (1952).

Cha32 J. Chadwick, Nature 129 312 (1932).

CPB77 L. Chaturverdi, C. N. Pandrey and S. K. Bose, IAEA Report, INDC(SEC)-61 123 (1977).

CSEWG Cross Section Evaluation Working Group, National Nuclear Data Center, Brookhaven National Laboratory.

DLM56 D. G. Dzantijev, V. N. Levkoskij and A. D. Malijevskij, Doklady Akademij Nauk SSSR 113 537 (1956).

DTH60 B. Diven, J. Terrell and A. Hemmendinger, Phys. Rev. 120 556 (1960).

ENDF Evaluated Nuclear Data File-B, Version VI. Available from the National Nuclear Data Center, Brookhaven National Laboratory. At the time of writing, a modification of the cadmium isotopic files is in progress. The primary changes are in the even-isotope resonance regions, employing the parameterizations of ref. [Wri93], the same resonance parameterizations used in this work (see Section II).

Fer91 N. Ferdous, Oxford Univ. Report, OUNP-91-18 (1991).

FG71 D. Foster and D. Glasgow, Phys. Rev. C3 576 (1971).

Fre76 J. Frehaut, Proc. Inter. Conf. on the Interaction of Neutrons with Nuclei, Editor E. Sheldon, CONF-760715-P1 (1976).

GC65 A. Gilbert and A. Cameron, Can. J. Phys. 43 1446 (1965).

Gib+63 J. Gibbons, R. Macklin, P. Metler and J. Neiler, Phys. Rev. 129 2695 (1963); see also Phys. Rev. 122 182 (1961).

GM71 L. Green and J. Mitchell, Proc. Conf. on Nucl. Data for Sci. and Technology, Knoxville, 1 325 (1971).

Gon+87 I. F. Goncalves et al., Rad. Applications and Instrumentation 38 989 (1987).

Hau68 T. Haugsness, Dissertation Abstracts B 28 3835 (1968).

Her+78 M. Herman et al., Nucl. Phys. A297 335 (1978).

HF52 W. Hauser and H. Feshbach, Phys. Rev. 87 362 (1952).

Hod71 P. E. Hodgson, Nuclear Reactions and Nuclear Structure (Clarendon, Oxford, 1971).

How93 R. J. Howerton, private communication (1993).

Joh+53 C. Johnson, H. Willard, J. Blair and J. Kington, Oak Ridge National Laboratory Report, ORNL-1365 (1953).

KH61 C. S. Khurana and H. S. Hans, Nucl. Phys. 28 560 (1961).

KH74 H. C. Kao and D. L. Humphrey Bull. Am. Phys. Soc. 19 700 (1974).

KNK79 K. Kayashimo, A. Nagao and I. Kumabe, NEA Report, NEANDC-61U (1979).
Kom69 D. Kompe, Nucl. Phys. A133 513 (1969).
Law92 R. D. Lawson, private communication (1992).
Lev63 V. N. Levkoski, J. Exp. Theo. Phys. 45 305 (1963).
LF69 W. D. Lu and R. W. Fink, Radiochimica Acta 12 61 (1969).
LF70 W. D. Lu and R. W. Fink, Bull. Am. Phys. Soc. 15 1372 (1970)
LRF70 W. D. Lu, N. Ranakumar and R. W. Fink, Phys. Rev. C1 358 (1970); see also D. Lu, N. Ranakumar and R. W. Fink, Phys. Rev. C1 350 (1970)
Mac+63 R. Macklin, J. Gibbons and T. Inada, Nucl. Phys. 43 353 (1963).
MDH81 S. Mughabghab, M. Divadeenam and N. Holden, Neutron Cross Sections (Academic, New York, 1981).
Mol80 P. A. Moldauer, Nucl. Phys. A344 185 (1980).
Mol81 P. A. Moldauer, The Coupled-Channels Code ANLECIS, private communication (1981); adaptation of the ECIS code of J. Raynal, NEA report (1979).
Mol82 P. A. Moldauer, Spherical Optical-Statistical Model Code ABAREX, private communication (1982); as modified by S. Chiba (1989).
MRK74 T. Manadat, S. A. Rao and P. K. Kurada, J. Inorgan. Nucl. Chem. 36 953 (1974).
Mus+82 A. Musgrove, B. Allen and R. Macklin, Nucl. Sci. and Eng. 82 230 (1982); see also J. Phys. G4 771 (1978) and Proc. Harwell Conf. on Neut. Phys. and Nucl. Data, NEA Press (1978).
NNDC National Nuclear Data Center, Brookhaven National Laboratory.
ND54 N. Nereson and S. Darden, Phys. Rev. 94 1678 (1954).
NDS D. de Frenne, E. Jacobs, M. Verboven and G. de Smit, Nucl. Data Sheets 53 73 (1988); R. L. Haese, F. E. Bertrand, B. Harmatz and M. J. Marten, Nucl. Data Sheets 37 289 (1982); P. de Gelder, E. Jacobs and D. de Frenne, Nucl. Data Sheets 38 545 (1983); J. Blachot and F. Haas, Ncul. Data Sheets 60 889 (1990); D. de Frenne, E. Jacobs and M. Verboven, Nucl. Data Sheets 57 443 (1989); J. Blachot, Nucl. Data Sheets 59 729 (1990); J. Blachot and G. Marguier, Nucl. Data Sheets 60 139 (1989); and J. Blachot and G. Marguier, Nucl. Data Sheets 59 333 (1990).
PAB85 R. Pepernik, B. Anders and B. M. Bahal, Proc. Conf. on Nucl. Data for Basic and Applied Science, Editors P. Young et al., (Gordon and Breach, New York, 1986).
PB61 R. J. Prestwood and B. P. Bayhurst, Phys. Rev. 121 1438 (1961).
PBS60 J. Peterson, A. Bratenahl and J. Stoering, Phys. Rev. 120 521 (1960).
Poe82 W. P. Poenitz, Argonne National Laboratory Report, ANL-83-4 (1982).
PP76 C. M. Perey and F. G. Perey, Atom Data and Nucl. Data Tables 17 1 (1976).
PS66 R. Parsad and D. C. Sarkar, Nucl. Phys. 85 476 (1966).

PW83 W. P. Poenitz and J. F. Whalen, Argonne National Laboratory Report, ANL/NDM-80 (1983).
Ray61 L. A. Rayburn, Phys. Rev. 122 168 (1961).
Ray63 L. A. Rayburn, Bull. Am. Phys. Soc. 8 60 (1963).
SG92 A. B. Smith and P. T. Guenther, Argonne National Laboratory Report, ANL/NDM-127 (1992).
Ste67 E. Steinness, Inst. Atom. Energi Report, KR-123 (1967).
SW54 S. Snowdon and W. Whitehead, Phys. Rev. 94 1267 (1954).
SW74 W. Struwe and G. Winkler, Nucl. Phys. A222 605 (1974).
TL66 K. Tsukada and T. Lee, Nucl. Phys. 83 274 (1966).
TW53 A. Taylor and E. Wood, Phil. Mag. 44 95 (1953).
VS66 W. Vonach and A. Smith, Nucl. Phys. 78 389 (1966).
WAL90 J. K. Tuli, Wallet Cards (National Nuclear Data Center, Brookhaven, New York, 1990).
Wal+53 M. Walt et al., Phys. Rev. 89 127 (1953).
WB55 M. Walt and J. Beyster, Phys. Rev. 98 677 (1955).
WG85 R. Walter and P. Guss, Proc. Conf. on Nucl. Data for Basic and Applied Science, Editors P. Young et al., (Gordon and Breach, New York, 1986).
Wic43 G. C. Wick, Atti R. Accad. Ital. Memorie 13 1203 (1943).
WMH75 H. Weigel, R. Michel and W. Hess, Radiochimica Acta 22 11 (1975).
Wri93 R. Q. Wright, June 1993 Meeting of the Am. Nucl. Soc.; to be published in Trans. Am. Nucl. Soc.
WS78 T. W. Woo and G. N. Salaita, Bull. Am. Phys. Soc. 23 526 (1978).
YAC92 P. G. Young, E. D. Arthur and M. B. Chadwick, Comprehensive Nuclear Model Calculations; Introduction to the Theory and Use of the GNASH Code, Los Alamos National Laboratory Report, LA-12343-MS (1992).
YG67 Yu-Wen and D. G. Gardner, Nucl. Phys. A98 451 (19676).

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