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ANL/NDM-72

Fast-Neutron Scattering from Elemental Cadmium

by

A.B. Smith and P.T. Guenther

July 1982

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

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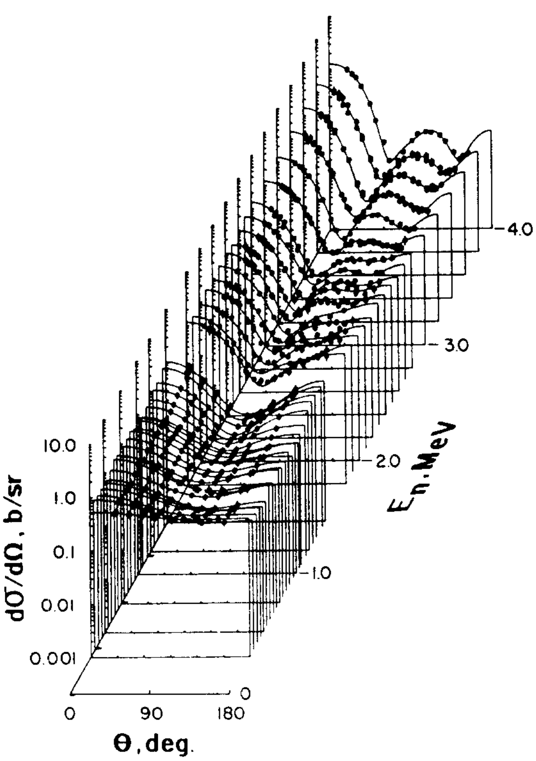

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*This work supported by the U.S. Department of Energy

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ANL/NDM-70 Fast-neutron Total and Scattering Cross Sections of Niobium by Alan B. Smith, Peter T. Guenther and James F. Whalen, July 1982.

ANL/NDM-71 Fast-neutron Total and Scattering Cross Sections of Elemental Palladium Alan B. Smith, P. T. Guenther and J. F. Whalen, June 1982.

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FAST-NEUTRON SCATTERING FROM ELEMENTAL CADMIUM

by

A. B. Smith and P. T. Guenther

Applied Physics Division

ABSTRACT

Neutron differential-elastic-scattering cross sections of elemental cadmium are measured from ≈ 1.5 to 4.0 MeV at incident-neutron energy intervals of 50 to 200 keV and at 10 to 20 scattering angles distributed between ≈ 20 and 160 degrees. Concurrently, lumped-level neutron inelastic-excitation cross sections are measured. The experimental results are used to deduce parameters of an optical-statistical model that is descriptive of the observables and are compared with corresponding quantities given in ENDF/B-V.

I. INTRODUCTION

This study of fast-neutron scattering from elemental cadmium is a part of a program with the objective of providing fast-neutron data and optical model (OM) parameters relevant to the light-mass fission-product region.

Elemental cadmium consists of eight isotopes; ^{106}Cd(1.3%), ^{108}Cd(0.9%), ^{110}Cd(12.5%), ^{111}Cd(12.8%), ^{112}Cd(24.1%), ^{113}Cd(12.2%), ^{114}Cd(28.7%) and ^{116}Cd(7.5%).[1] The majority consists of even isotopes having similar low-lying excited structures. The fission-product yields of these isotopes are not large (e.g., ranging from 0.18%(^{110}Cd) to 0.052%(^{114}Cd) for thermal-neutron-induced fission of ^{239}Pu). However, the isotopes are at the upper-mass extreme of the light-mass fission-yield distribution and thus are useful reference points in the derivation of "regional" OM parameters. This report presents the results of an experimental study of fast-neutron scattering from elemental cadmium and the derivation of OM parameters therefrom.

II. OUTLINE OF THE EXPERIMENTAL METHOD

The measurement sample was a cylinder of metallic cadmium 2 cm in diameter and 2 cm long. Its density was determined by precise weight and dimension measurements. All of the scattering measurements employed the time-of-flight technique and the Argonne ten-angle velocity spectrometer.[2] The neutron source was the ^{7}Li(p,n)^{7}Be reaction pulsed on for durations of $\approx$ 1 nsec at a repetition rate of 2 MHz. The scattering sample was placed $\approx$ 13 cm from the source at a zero-degree reaction angle. Ten flight paths, distributed over the angular range 20 to 160 degrees, were focused on the sample. The relative scattering angles were known to $\pm$ 0.2 degrees and the absolute angular scale to within $\pm$ 0.6 degrees.

The scattered neutrons were detected with proton-recoil scintillators placed $\approx$ 5.4 m from the scattering sample. An additional time-of-flight detector monitored the source intensity. The relative energy-dependent sensitivities of the detectors were determined by observing neutrons emitted at the spontaneous fission of ^{252}Cf.[3] These relative sensitivities were normalized to the measured neutron total cross sections of carbon using the method described in Ref. 4. The cross sections were deduced from the measured velocity spectra and were corrected for multiple-event, beam-attenuation and angular-resolution effects as described in Ref. 5.

III. EXPERIMENTAL RESULTS

The measurements were made over the range 1.5 to 4.0 MeV. Below 3.0 MeV the differential results were obtained at $\approx$ 50 keV intervals and at ten scattering angles. Above 3.0 MeV the measurement interval was 200 keV and twenty scattering angles were used. The primary objective was accurate energy-averaged elastic-scattering cross sections, thus broad (40 to 70 keV) incident-energy spreads were used. These were not a limitation in the definition of elastic-scattering cross sections as none of the cadmium isotopes have excited levels at energies less than ≈ 200 keV.[1] In order to enhance the accuracies of the elastic-scattering results and smooth any residual fluctuations, differential values obtained at adjacent energies were averaged below 3.0 MeV. The broad-incident-energy spreads did inhibit the detailed resolution of inelastic-scattering neutron groups but these were not a primary measurement objective.

The experimental-differential-elastic-scattering results are summarized in Fig. 1. The uncertainties associated with these differential values are $\lesssim$ 5% excepting a few values near the extreme minima of the distributions. The origins of the uncertainties are; $\lesssim$ 1% due to statistics, $\lesssim$ 3% due to detector calibration and normalization procedures, and $\lesssim$ 1% as a consequence of correction procedures. These uncertainty estimates were supported by comparing concurrently-measured carbon-elastic-scattering cross sections with those reported in the literature.[6] The angle-integrated elastic-scattering cross sections were deduced from the measured differential values by least-square fitting 6^{th}-order Legendre-Polynomial series to the experimental values. The resulting angle-integrated values are shown in Fig. 2. The indicated uncertainties are 5%. The present results are in good agreement with lower-energy elastic-scattering values previously reported from this laboratory[7], as illustrated in Fig. 2. More generally, the prior data base should be reasonably summarized by ENDF/B-V.[8] Comparisons of the present results with those from that evaluation are discussed below.

The many cadmium isotopes and the broad incident energy spreads (cited above) limited the definition of inelastic scattering in the present work. However, energy-broad inelastically-scattered-neutron groups were identified corresponding to the excitation energies given in Table. 1. The corresponding angle-integrated inelastic-scattering cross sections were derived from the differential values by fitting Legendre-Polynomial series as described for elastic scattering. The results are outlined in Fig. 3. The origin of the illustrated uncertainties is analogous to that defined above for elastic scattering, with much-larger statistical components. In addition, most of the values relevant to the excitation of the 594-keV level were subject to large corrections for elastically-scattered neutrons originating in the second group of the neutron-source reaction. Comparisons with Ref. 1 suggest that the observed 594-keV excitation is primarily due to contributions from the first 2+ levels of the even cadmium isotopes. The other two observed inelastically-scattered neutron groups appear to be due to a number of components too complex to make possible quantitative comparisons with reported levels in the various isotopes. The present results for the excitation of the 594-keV level are qualitatively consistent with the lower-energy values of Ref. 7, as illustrated in Fig. 3. More generally, the present neutron scattering results are consistent with the neutron total cross sections of Ref. 9. This suggests that very nearly all of the inelastic-scattering due to excitations of $\lesssim$ 2.0 MeV is represented by the present broad-resolution measurements. However, this is a qualitative conclusion since the present work was not intended to be a definitive study of the inelastic-scattering cross sections of elemental cadmium.

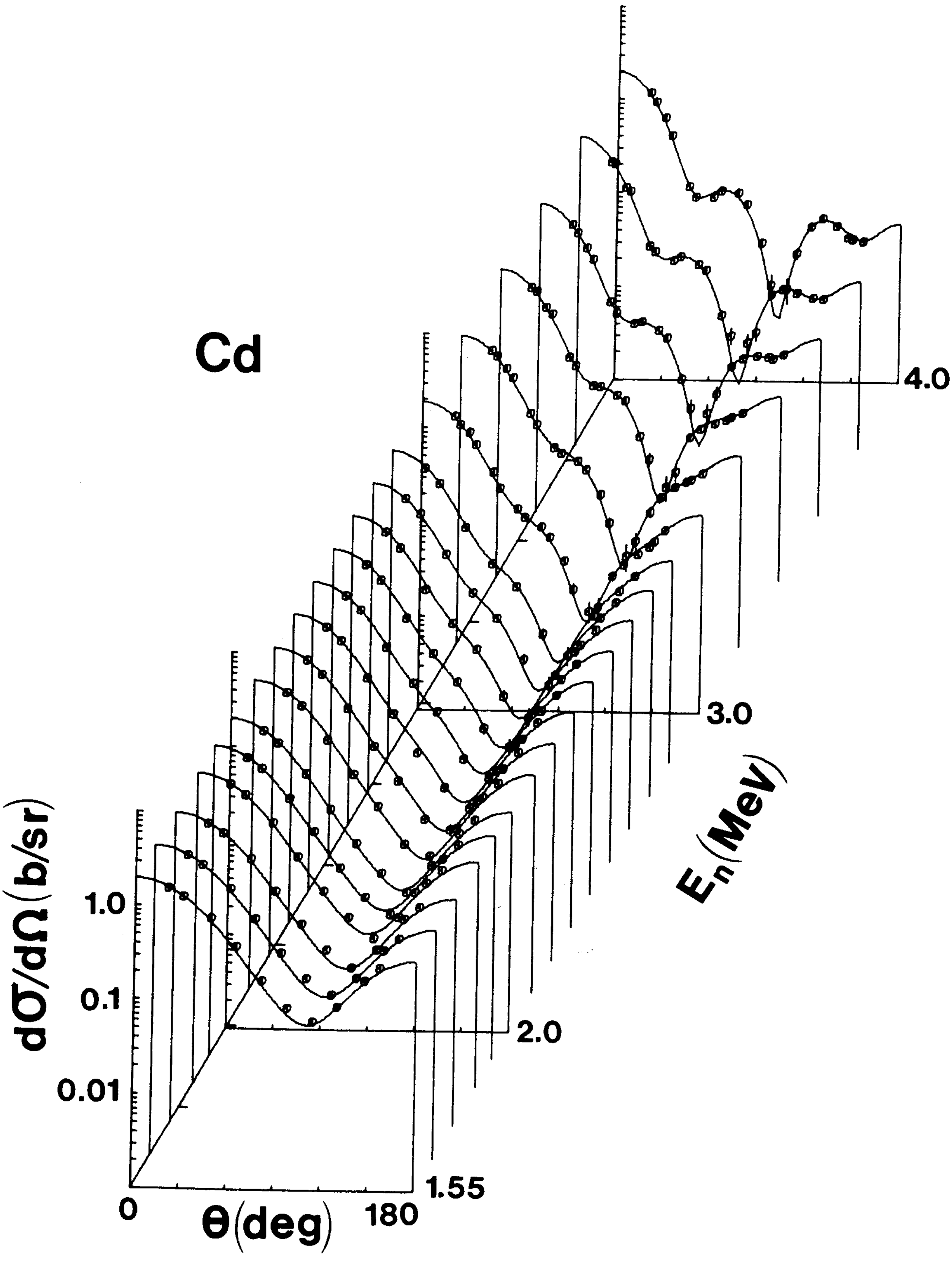

Fig. 1. Differential-Elastic-Scattering Cross Sections of Elemental Cadmium. The measured values are indicated by data symbols and the results of Legendre-Polynomial fits to the data by curves.

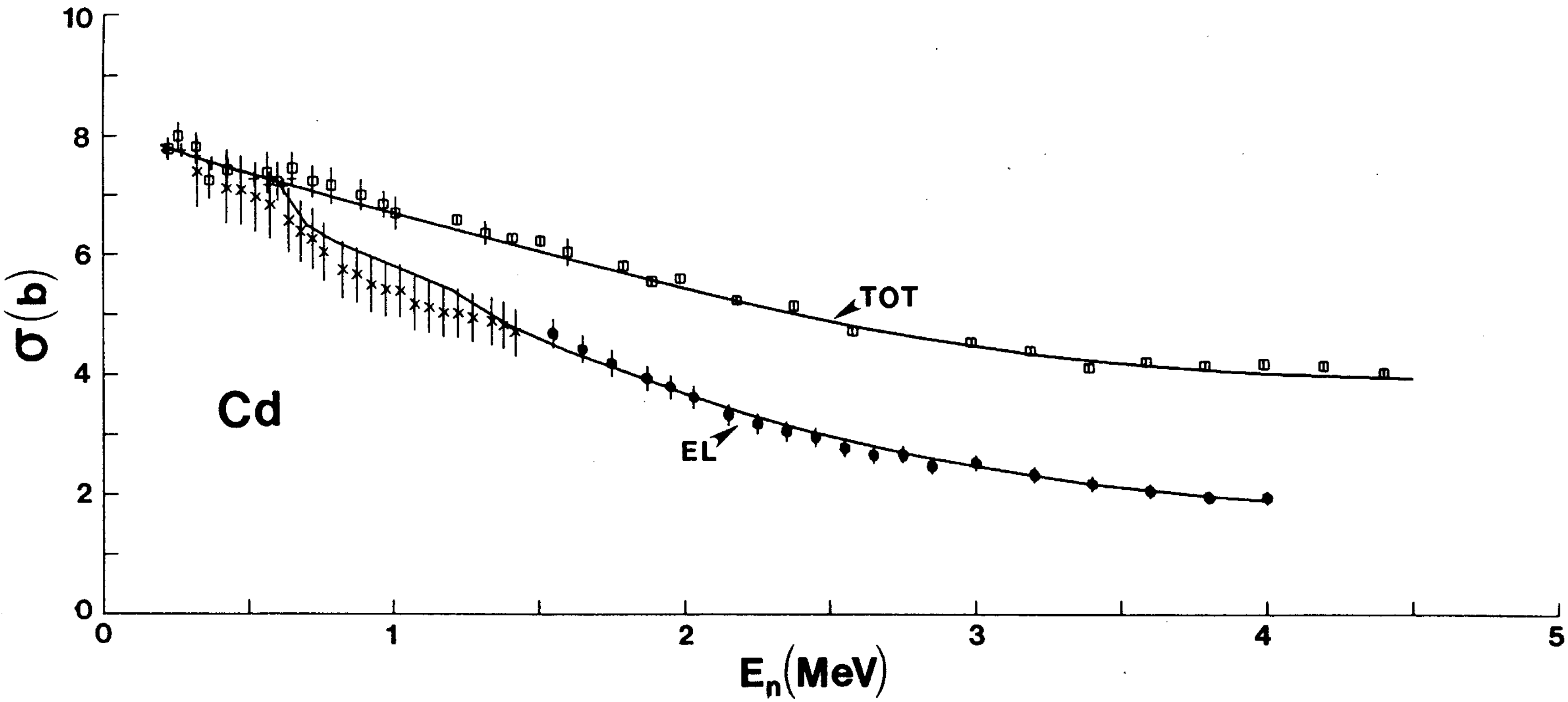

Fig. 2. Comparison of measured (symbols) and calculated (curves) neutron total and elastic-scattering cross sections. Measured total cross sections given by; □ = present work above 1.0 MeV and 50 keV average of Ref. 9 at lower energies, + = 50 keV average of Ref. 10; elastic-scattering by ● = present work and x = Ref. 7.

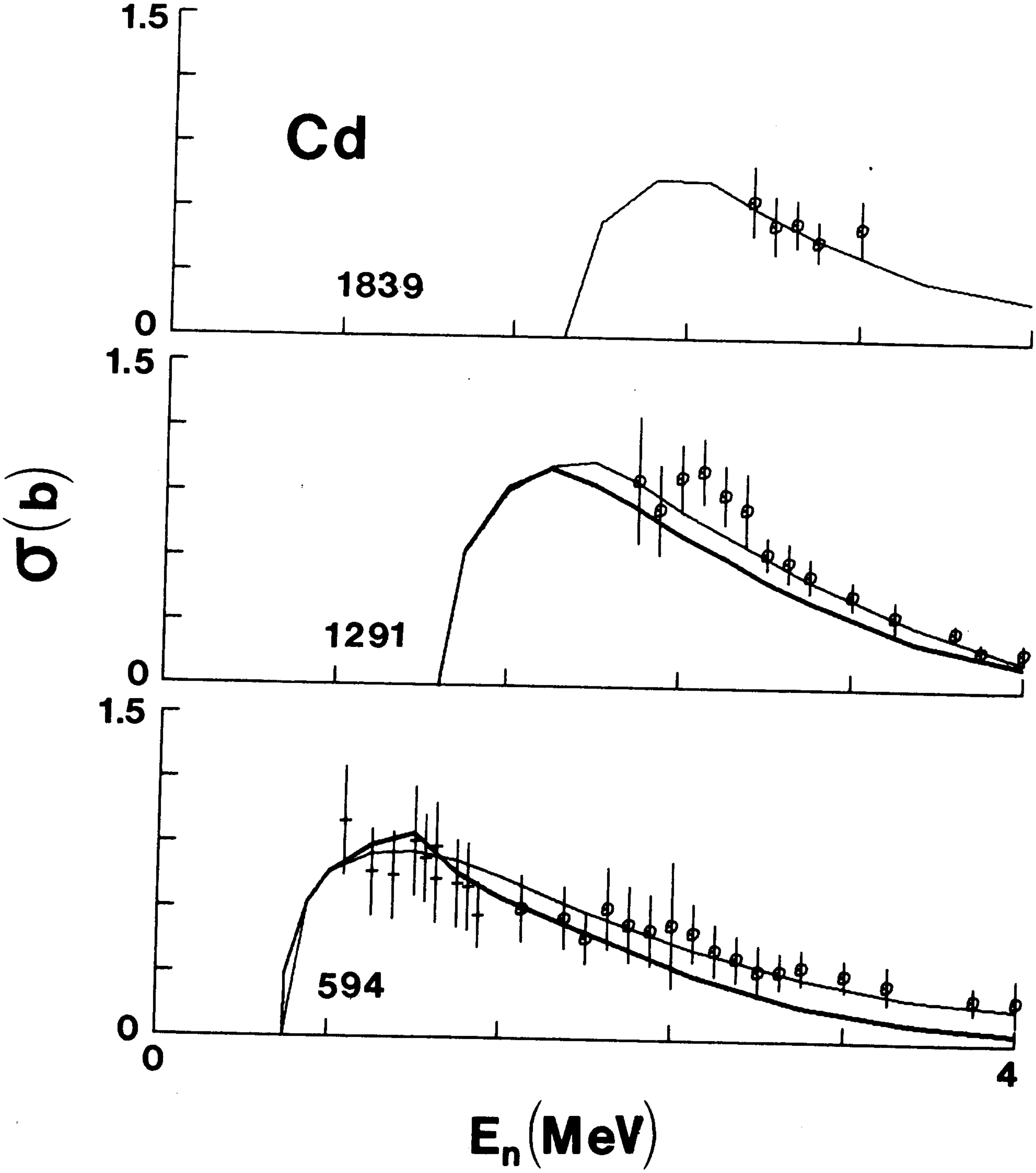

Fig. 3. Lumped-level inelastic excitation cross sections of elemental cadmium. the present experimental results are indicated by ○ and those of Ref. 7 by +. Light curves are "eyeguides" and heavy curves indicate the results of calculations as outlined in the text.

IV. INTERPRETATION

It was assumed that the observed cross sections could be reasonably-well described by a conventional optical-statistical model (OM).[11] The measurements extended over an energy region where compound-nucleus (CN) processes are prominent. These were calculated using the Hauser-Feshbach formula[12] as modified by Moldauer.[13] There are a number of isotopes of cadmium with about three quarters of the elemental abundance due to even nuclei. These even nuclei have similar low-lying level structure[1] and that of ^{114}Cd appears to be the best known. Thus it was assumed that the elemental level structure could be represented by ^{114}Cd. Contributions to the CN process due to the minority ($\approx$ 25% abundant) odd isotopes should not markedly effect the calculation of neutron total and/or elastic-scattering cross sections in the energy region of the present measurements. The excitation of levels up to $\approx$ 1.75 MeV was explicitly calculated using the energetics and J-Π values of Ref. 1. Contributions due to higher-lying levels were calculated using the statistical formulation and parameters of Gilbert and Cameron.[14] All of the calculations employed the spherical OM code ABAREX.[15]

With the above assumptions the measured differential-elastic-scattering cross sections (Fig. 1) were concurrently chi-square fitted by simultaneously varying the six OM parameters; real and imaginary strengths, radii and diffusenesses. The energy range of the present measurements was not sufficient to reasonably define the parameter energy dependences. Therefore the energy-dependence of the real strength was assumed to be $V = V_0 - 0.3 \cdot E$ (MeV)[16], and the remainder of the parameters were taken to be energy independent. An additional assumption was a 6 MeV spin-orbit potential of the Thomas form. The fitting procedure converged quite rapidly to yield the parameters of Table 2. These parameters provide a good description of the observed differential-elastic-scattering distributions, as illustrated in Fig. 4, and of the neutron total and angle-integrated elastic-scattering cross sections, as illustrated in Fig. 2. There is some difference between measured and calculated elastic-scattering cross sections well below the energies of the present work. This is due to the influence of low-lying levels of the odd isotopes which were not included in the present calculations. The parameters of Table 2 were also used to calculate the neutron inelastic-excitation cross sections, again assuming ^{114}Cd was representative of the element. The results are in reasonable agreement with the measured values (see Fig. 3), considering the experimental uncertainties and the calculational approximations. There is a tendency for the calculated inelastic-scattering cross sections to be smaller than the measured values in a manner that could be attributable to inappropriate statistical-level parameters. However, the inelastic-scattering aspects of the present work are not sufficiently quantitative to provide much guidance as to statistical-level parameters.

V. COMPARISONS WITH ENDF/B-V

The present elastic-scattering results and the neutron total-cross-section results of Refs. 9 and 10 are directly comparable with ENDF/B-V[8] values. The

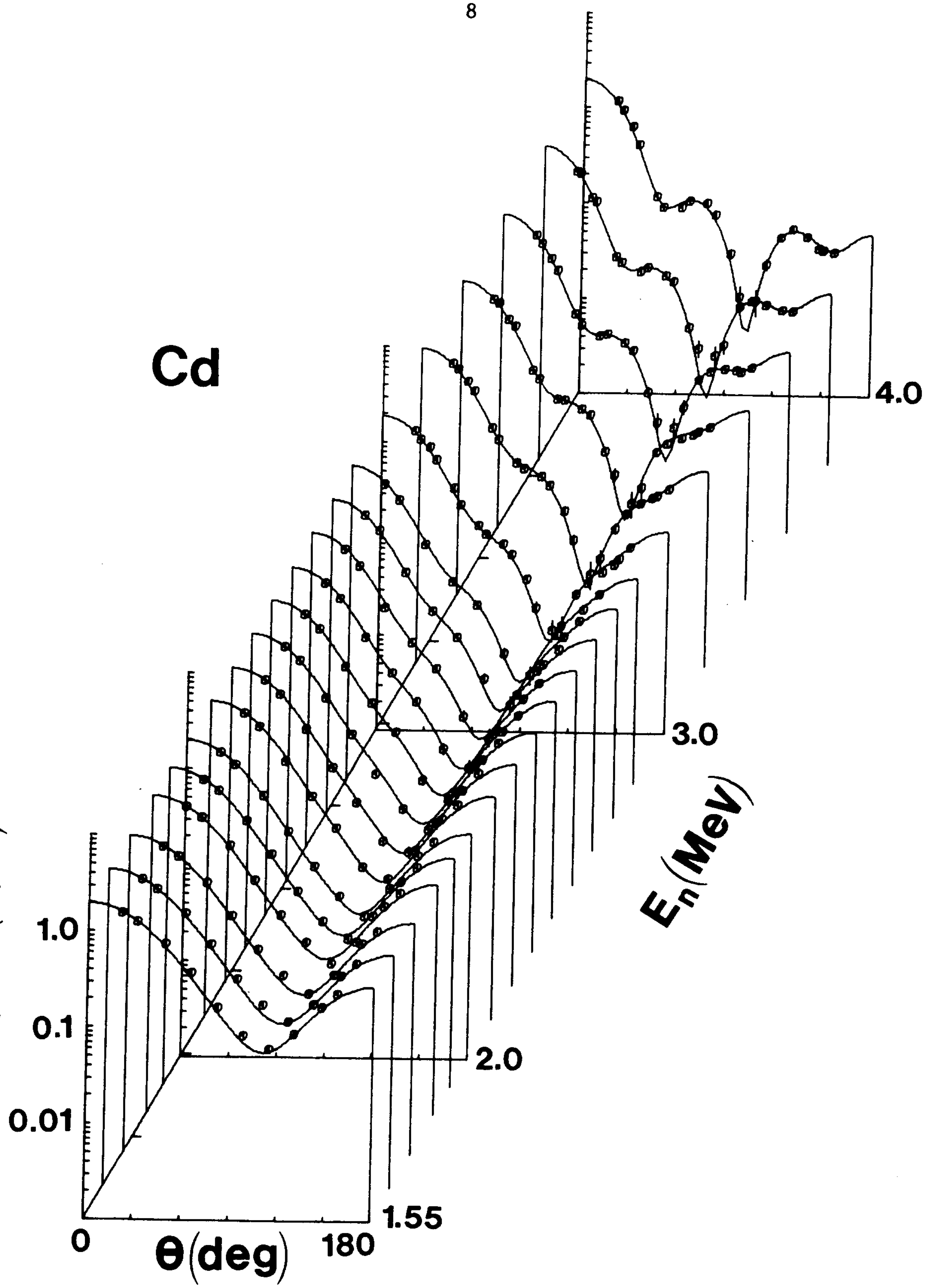

Fig. 4. Comparison of measured and calculated differential-elastic-scattering cross sections of elemental cadmium. The experimental results are indicated by symbols and the calculated values by curves.

present angle-integrated elastic-scattering results and the lower-energy values of Ref. 5 are in reasonable agreement with ENDF/B-V, as illustrated in Fig. 5. The differences between the measured and evaluated quantities are seldom beyond the experimental uncertainties. Above several MeV, the evaluated and measured neutron total cross sections are also reasonably consistent (see Fig. 5). However, below 2 MeV the measured neutron total cross sections are up to 5-7% larger than the evaluated quantities and the evaluated cross section shows some structure not evident in the measured values. This low-energy region is important for the understanding of fission-product capture. The present lumped-level inelastic-scattering results are not simply related to the evaluated inelastic-scattering cross sections therefore detailed comparisons were not attempted.

VI. CONCLUDING REMARKS

The present experimental results improve the understanding of elastic neutron scattering from elemental cadmium in the few-MeV region. These results are used to deduce a spherical optical-statistical model that is descriptive of both the present measured elastic-scattering results and of lower-energy elastic-scattering and neutron total cross sections previously determined at this Laboratory. The model parameters provide information useful for the development of a general optical-statistical model applicable to the light fission-product region, to be reported elsewhere.[17]

ACKNOWLEDGEMENTS

The authors are indebted to Drs. W. Poenitz and P. Moldauer for helpful discussions and for the provision of pre-publication data.

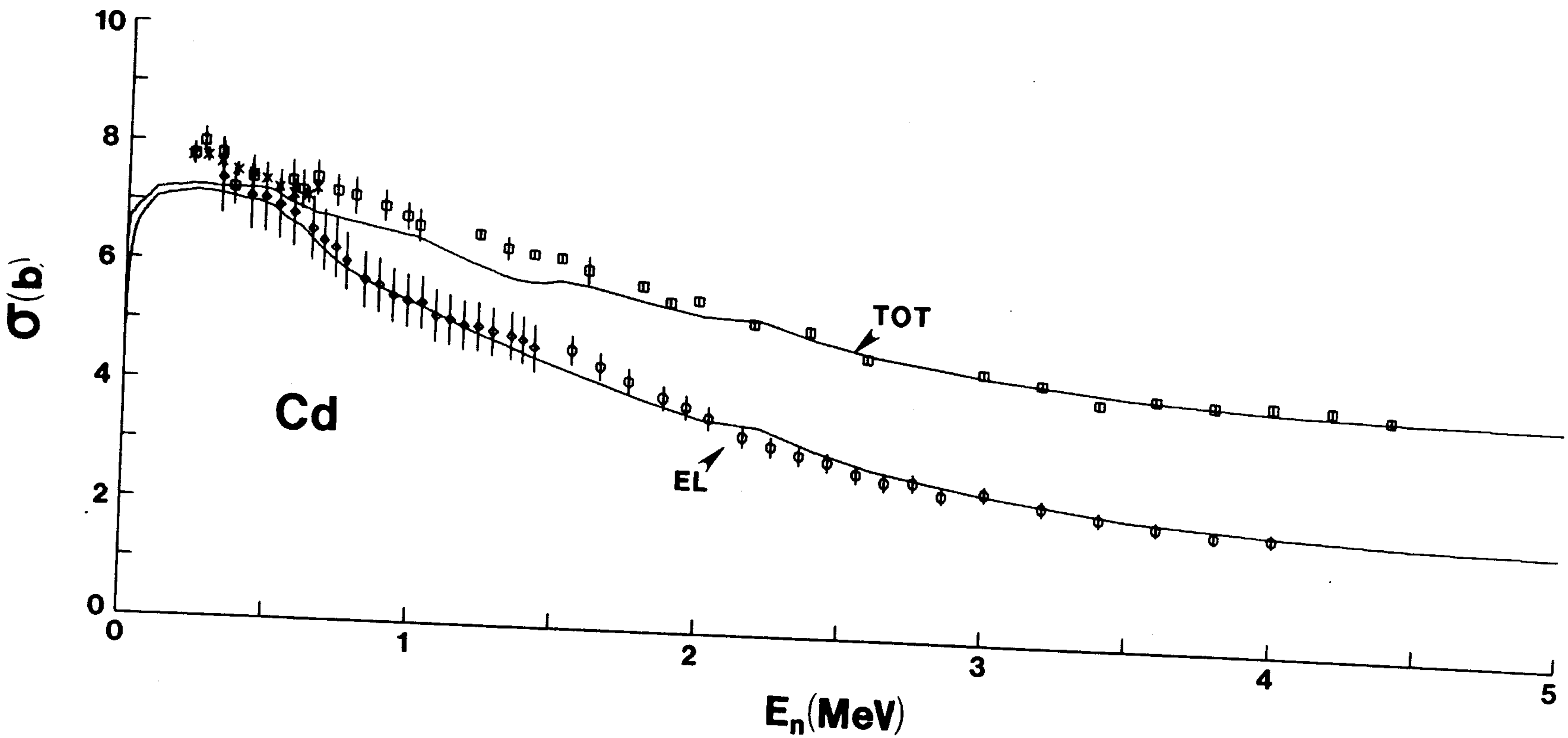

Fig. 5. Comparison of measured (data symbols) and evaluated (curves) neutron total and elastic-scattering cross sections of elemental cadmium. The measured values are those referenced in Fig. 2 and the evaluation is ENDF/B-V.[8]

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Table 1. Observed Neutron Excitation Energies

No.	E_x (keV)
1	594 ± 10[a]
2	1291 ± 66
3	1839 ± 57

[a]Uncertainties defined as RMS deviations from the simple average of a number of measurements.

Table 2. Spherical Optical-Model Parmaeters for Elemental Cadmium

Real Potential[a]		
Strength	V_o = 48.82	MeV
Radius[b]	r_v = 1.247	F
Diffuseness	a_v = 0.599	F
J_v/A = 435.0	MeV x F^3	
$V_o r^2$ = 75.88	MeV x F^2	
Imaginary Potential[c]		
Strength	W = 7.373	MeV
Radius	1.193	F
Diffuseness	0.5945	F
J_w/A = 67.21	MeV x F^3	
Wa = 4.38	MeV x F	

[a]Saxon form, assume $V = V_o - 0.3\,E(\text{MeV})$ and a 6 MeV spin-orbit strength of the Thomas form.

[b]All radii expressed as $R = r \times A^{1/3}$.

[c]Saxon-derivative form.