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ANL/NDM-76

Scattering of Fast-Neutrons from Elemental Molybdenum

by

A.B. Smith and P.T. Guenther

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ARGONNE NATIONAL LABORATORY,
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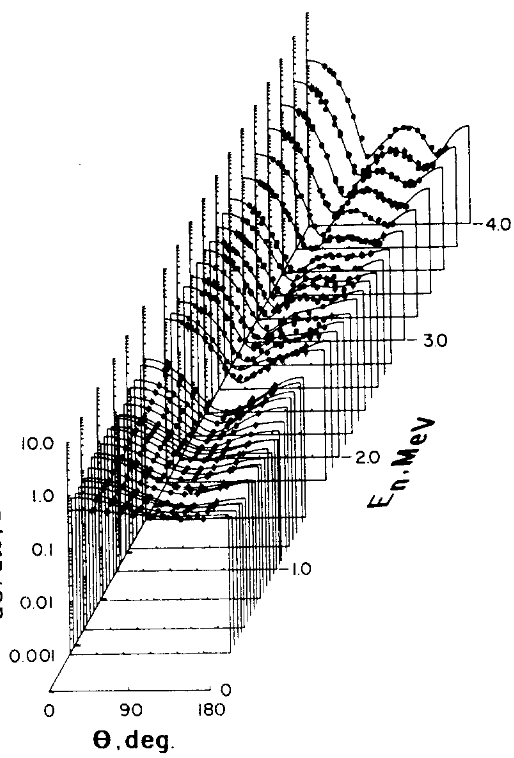

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SCATTERING OF FAST-NEUTRONS FROM ELEMENTAL MOLYBDENUM*

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SCATTERING OF FAST-NEUTRONS FROM ELEMENTAL MOLYBDENUM

by

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ABSTRACT

Differential broad-resolution neutron-scattering cross sections of elemental molybdenum were measured at 10-20 scattering angles distributed between 20 and 160 degrees and at incident-neutron energy intervals of ≈ 50-200 keV from 1.5 to 4.0 MeV. Elastically-scattered neutrons were fully resolved from inelastic events. Lumped-level inelastic-neutron-scattering cross sections were determined corresponding to observed excitation energies of; 789±23, 1095±23, 1500±34, 1617±12, 1787, 1874, 1991, 2063±24, 2296, 2569 and 2802 keV. An optical-statistical model was deduced from the measured elastic-scattering results. The experimental values were compared with the respective quantities given in ENDF/B-V.

I. INTRODUCTION

The present study is a part of a comprehensive investigation of the fast-neutron interaction with light fission-product nuclides including the experimental determination of fast-neutron total and scattering cross sections.[1-6] Elemental molybdenum consists of seven isotopes; ^{92}Mo(14.8%), ^{94}Mo(9.3%), ^{95}Mo(15.9%), ^{96}Mo(16.7%), ^{97}Mo(9.6%), ^{98}Mo(24.1%) and ^{100}Mo(9.6%).[7] The majority of these are even-even nuclides. One (^{92}Mo) is magic in neutron number. Some of these isotopes show the characteristics of collective-vibrational and/or -rotational nuclides.[8] Fission yields are large; typically ^{92}Mo(6.2%), ^{94}Mo(6.5%), ^{95}Mo(6.6%), ^{96}Mo(6.6%), ^{98}Mo(6.0%) and ^{100}Mo(6.4%) for fission-neutron induced fission of ^{235}U.

The objectives of the present work were the explicit provision of fast-neutron-scattering cross sections of elemental molybdenum and the deduction of an optical-statistical model (OM) useful in the subsequent formulation of a generalized OM applicable to light fission products.[9] Subsequent portions of this report deal with: a brief outline of the experimental method (Sec. II), the experimental results (Sec. III), the derivation of an OM from the measured elastic-scattering results (Sec. IV), and some comparisons with corresponding values given in ENDF/B-V (Sec. V)[10].

II. OUTLINE OF EXPERIMENTAL METHOD

The neutron-scattering measurements were made using the time-of-flight technique and the Argonne ten-angle detection apparatus.[11] 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 neutron source at a zero-degree source-reaction angle. The scattering sample was a solid metal cylinder fabricated of chemically pure elemental molybdenum, 2 cm in diameter and 2 cm long. Its density was determined by precise weight and dimension measurements. The ten neutron detectors were proton-recoil scintillators. They were placed $\approx$ 5.4 m from the scattering sample within massive collimators distributed over the scattering-angle range $\approx$ 20-160 degrees. The scattering angles were known to $\lesssim\pm$ 0.6 degrees. An eleventh time-of-flight detector was used to monitor the source intensity. The relative detector sensitivities were determined by observing neutrons emitted from the spontaneous fission of ^{252}Cf.[12] These relative sensitivities were normalized to the neutron total cross sections of carbon in the manner described in ref. 13. All of the measured differential-scattering cross sections were corrected for multiple-event, beam-attenuation and angular-resolution effects as described in ref. 14. Details of the method and the apparatus are given in ref. 14.

III. EXPERIMENTAL RESULTS*

The measurements were made at incident-neutron energies from 1.5 to 4.0 MeV, at intervals of ≈ 50 keV below 3.0 MeV and at intervals of ≈ 200 keV at higher energies. The mean incident-neutron-energy scale was known to ≈ 10 keV. The incident-neutron-energy spread was ≈ 50 to 80 keV. These relatively-broad incident-energy spreads were chosen in order to smooth possible energy-dependent structure. Below 3.0 MeV the measurements were made at ten scattering angles. At higher incident-neutron energies twenty scattering angles were used.

A. Neutron Elastic-Scattering Cross Sections

The scattered-neutron resolution was sufficient to resolve the elastic-scattering component from all known inelastic-scattering contributions. Below 3.0 MeV the differential-elastic-scattering cross sections measured at adjacent incident energies were averaged in order to reduce the effects of any possible fluctuations. The energy-averaged results are summarized in Fig. 1 and behave in an energy-smooth manner. The statistical uncertainties of the individual differential values are $\lesssim$ 1%, excluding the extreme minima of the distributions. The detector normalizations were known to ≈ 3% and the correction procedures generally introduced an additional $\lesssim$ 1% uncertainty. Thus the overall differential-elastic-scattering cross section uncertainties are $\lesssim$ 5%. The angle-integrated elastic-scattering cross sections were derived from the measured differential values by least-square fitting the data with a 6^{th}-order Legendre-polynomial series. The quality of the fitting results is illustrated in Fig. 1. The resulting angle-integrated elastic-scattering cross sections are shown in Fig. 2. The angle-integrated elastic-scattering cross section uncertainties are $\lesssim$ 5%.

The present angle-integrated elastic-scattering results reasonably extrapolate to the lower-energy values of ref. 8. The present differential-elastic-scattering cross sections are reasonably consistent with the isotopic values of ref. 17 as illustrated by Section IV, below. Generally, the ENDF/B-V[10] evaluation should be representative of prior knowledge. The present elastic-scattering results are compared with the evaluated quantities of ref. 10 in Section V.

B. Neutron Inelastic-Scattering Cross Sections

Some knowledge of the inelastic-scattering process was obtained as a bi-product of the primary elastic-scattering measurements. The low-lying level structure of elemental molybdenum is very complex due to the profusion of quite abundant isotopes of both odd and even A. This complexity, and the

*The numerical data reported herein has been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory.

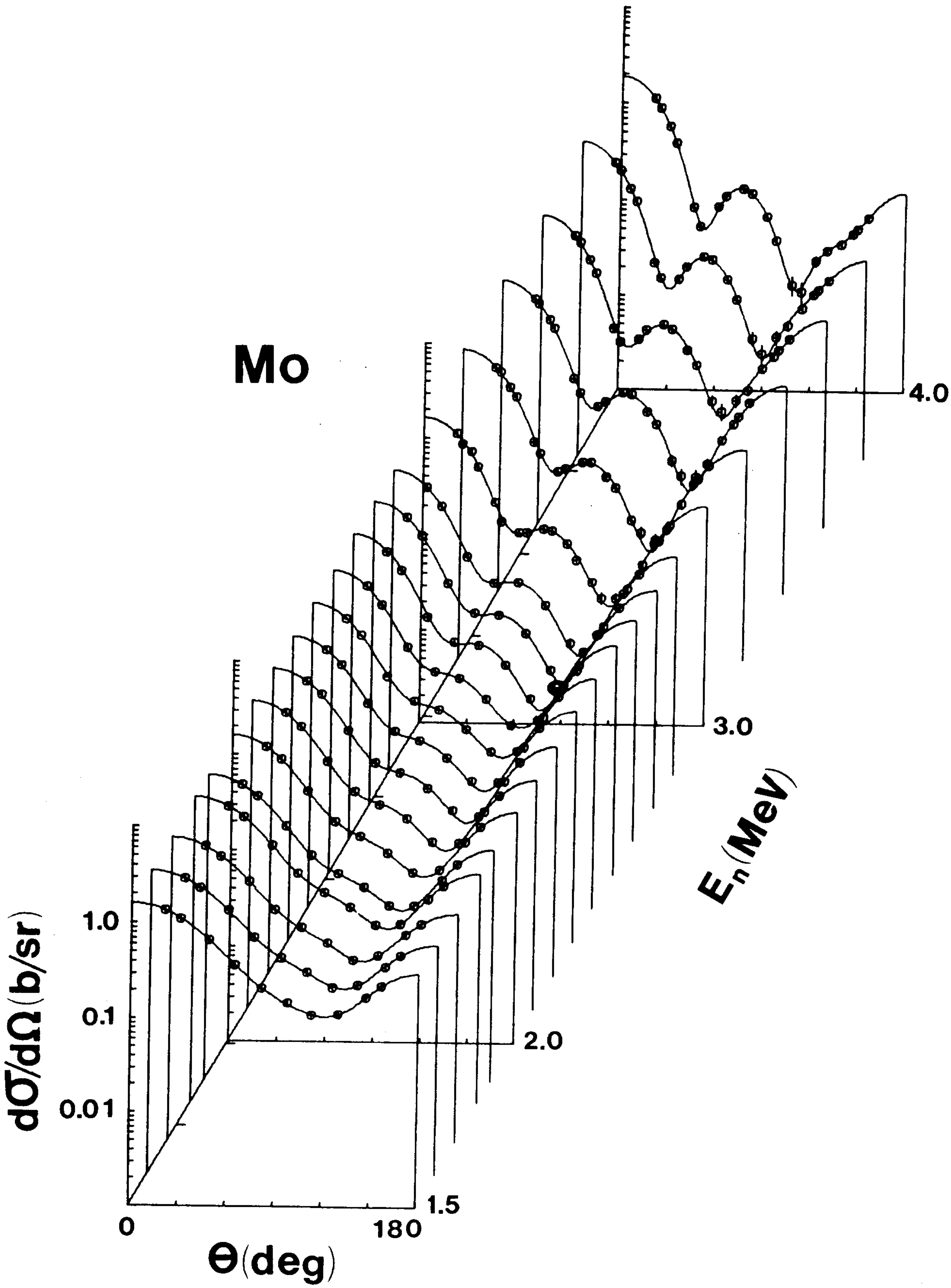

Fig. 1. Differential Neutron-Elastic-Scattering Cross Sections of Elemental Molybdenum. Data symbols indicate experimental values and curves the results of fitting Legendre-polynomial series to the measured values (in lab. coordinates).

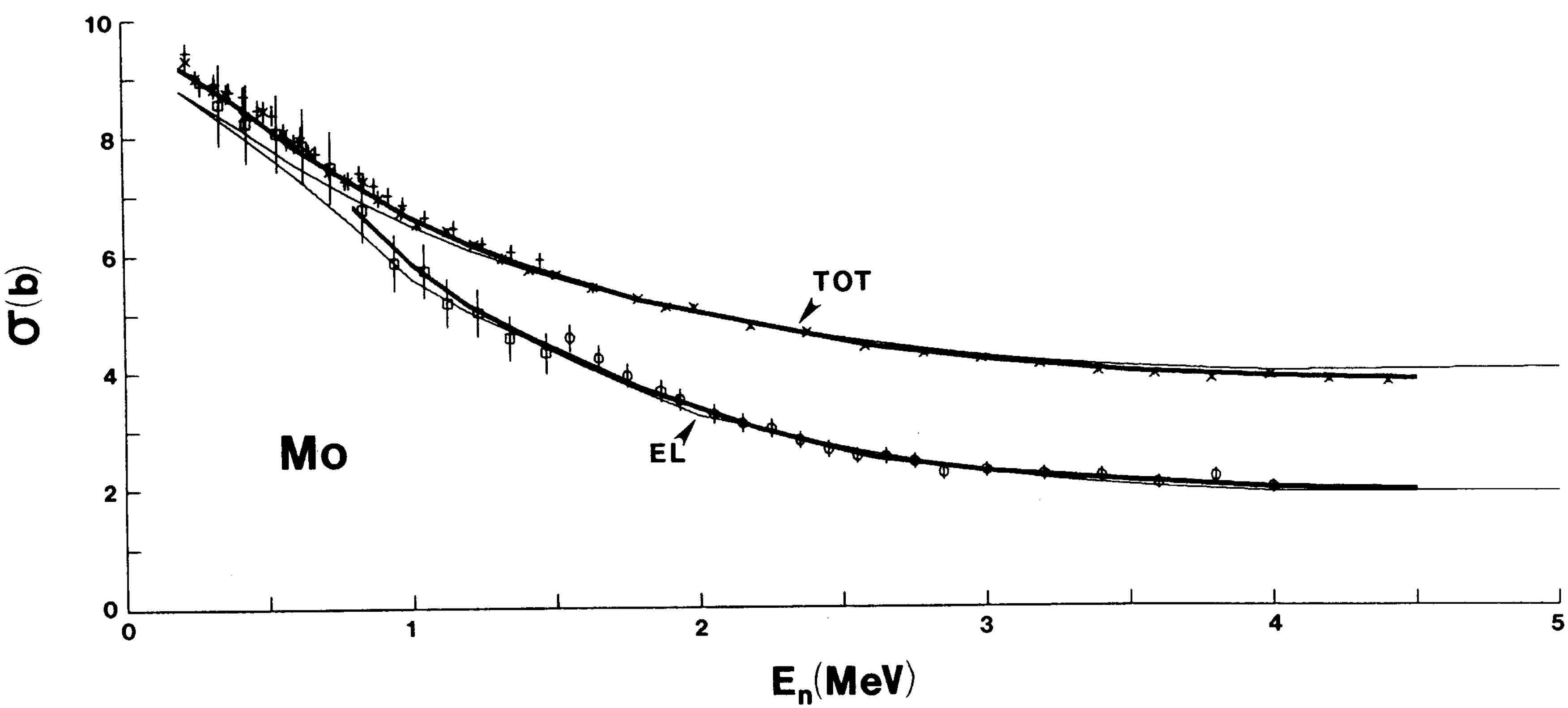

Fig. 2. Neutron Total and Elastic-Scattering Cross Sections of Elemental Molybdenum. Data symbols denote measured values; 0 = present results, □ = ref. 8, X = ref. 15 and + = ref. 16. Heavy curves are "eyeguides" through the measured values. Light curves indicate the results of calculations as described in the text.

intentionally-broad resolutions employed in the present work, precluded detailed resolution of the inelastic-scattering processes. However, prominent features of the inelastic-scattering process were evident. Notable among these were observed neutron excitation energies of 789±23, 1095±23 and 1500±34 keV. An inspection of ref. 7 indicates that each of these is a composite of a number of contributions from various of the isotopes. Beyond these three prominent inelastic groups, nine excitations were tentatively or marginally identified as outlined in Table 1. All appear to be composites of a number of contributions from various isotopes. One group (E_x = 1240 keV) was entirely attributed to the second-neutron component from the $^7Li(p;n)^7Be$ source reaction. That second component obscured excitations in the range 400 to 500 keV and may have distorted some of the other higher-energy excitations.

In view of the above, only the data relevant to the prominent 789, 1095 and 1500 keV excitations were reduced to cross sections, leading to the angle-integrated results shown in Fig. 3. The uncertainties have the same origins as cited above for elastic scattering, with larger statistical components. The differential inelastic-neutron angular distributions were nearly isotropic and the angle-integrated cross sections were derived by fitting P_2 Legendre-polynomial series to the measured values. More definitive measurement of inelastic-scattering cross sections probably would require use of isotopic samples, as described in ref. 17. The latter isotopic elastic-scattering results are reasonably consistent with the present values. Furthermore, the present elastic- and inelastic-scattering results are consistent with the recently-measured neutron total cross sections of ref. 15, though there are large uncertainties associated with the higher-energy excitations of Table 1.

IV. INTERPRETATION

An objective of the present work was an OM[18] applicable to the present measurements and to this mass-energy region generally. The formulation of such an OM from the present elemental results was complicated by the number of contributing isotopes, some with quite difference excited levels.[7] The present interpretation proceeded in an iterative manner. Initially, an assumed OM potential was used to calculate the compound-elastic-scattering (CE) cross sections for each of the isotopes. These calculations used the discrete level structure of ref. 7 and the statistical formalism and parameters of Gilbert and Cameron[19] for representing the higher-energy continuum levels. The calculations were based upon the Hauser-Feshbach formula,[20] as modified by Moldauer,[21] and carried out with the computer code ABAREX.[22] The isotopic CE values were combined to obtain elemental CE cross sections which were subtracted from the measured differential-elastic-scattering cross sections to obtain the "measured" differential shape-elastic-scattering (SE) cross sections. The OM parameters were then determined by concurrently chi-square fitting all the "measured" SE cross sections assuming an average target mass and simultaneously varying the six OM parameters; real and imaginary strengths, radii and diffusenesses. A spin-orbit potential of the Thomas form, with a 6 MeV strength, was assumed. In addition, the real potential was assumed to have an energy dependence of

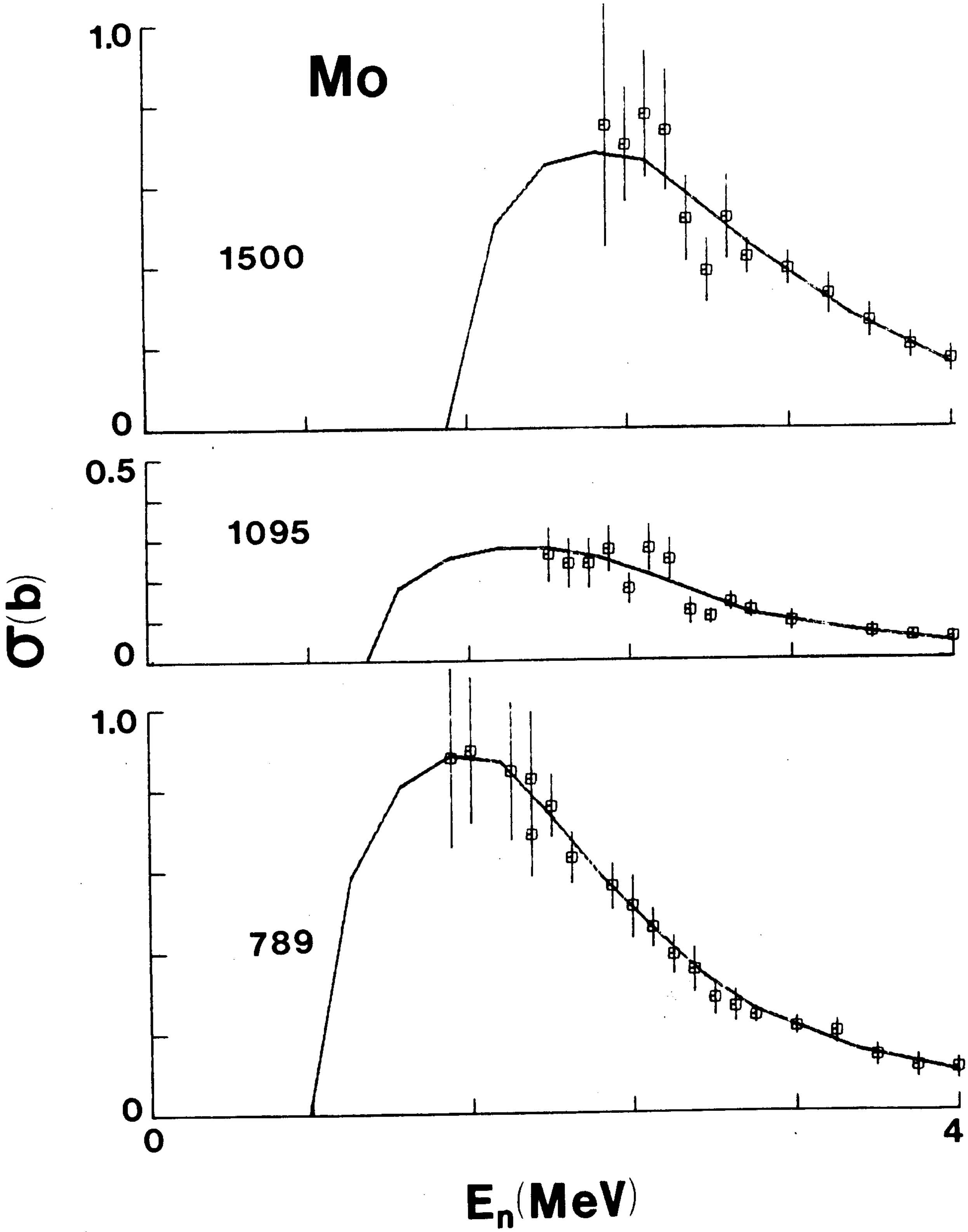

Fig. 3. Some Neutron Inelastic-Excitation Cross sections of Elemental Molybdenum. Data symbols indicate the present measured values and curves "eyeguides" through the experimental values. Observed excitation energies (in keV) are numerically noted in the respective portions of the figure.

the form $V = V_o - 0.3 \bullet E(MeV)$, in accord with the results of higher-energy studies.[23] The OM parameters resulting from the SE fitting were used to recalculate CE and SE cross sections and the fitting procedure was repeated. The process was iterated through four cycles. The third and fourth cycles resulted in essentially the same parameters and quality of fit to the "measured" differential-shape-elastic-scattering cross sections. Thus the parameters of the fourth iteration were accepted as final values. They are given in Table 2.

The parameters of Table 2 provide a good description of the measured differential-elastic-scattering cross sections, as illustrated in Fig. 4. There are small differences between measured and calculated results at the lowest energies of the present work but that region is subject to experimental and computational uncertainties due to resonance fluctuations. The parameters also give a fairly good description of the angle-integrated elastic-scattering cross sections and of the neutron total cross sections of ref. 15, as illustrated in Fig. 2. At energies well below those of the present work the calculated results are a few percent lower than the measured values but that is a region where, particularly for ^{92}Mo, the cross sections are known to fluctuated by large amounts.[24] The parameters of Table 2 also provide a reasonably good description of the isotopic differential-elastic-scattering cross sections of ref. 17, as illustrated by the ^{92}Mo example of Fig. 5. These comparisons of measured and calculated elemental and isotopic differential-elastic-scattering cross sections imply consistency between elemental and isotopic experimental values.

The parameters of Table 2 are relatively conventional. They do include a large imaginary radius characteristic of potentials based upon strength-function analysis[25] though strength functions were not involved in the present considerations. The potential strengths, measured as the integral per nucleon (J/A), are fairly consistent with the isotopic values of ref. 17 (e.g. J_v/A of the present work is ≈ 2% larger than that of ref. 17). The above fitting procedures were applied to the ^{92}Mo, ^{96}Mo, ^{98}Mo and ^{100}Mo isotopic differential-elastic-scattering cross sections of ref. 17 with the results indicated in the footnote of Table 2. The data of ref. 17 are not as accurate as those of the present work, but the J_v/A values are in reasonable agreement with those derived from the present elemental results. The imaginary strengths are in similar agreement excluding that for ^{92}Mo. ^{92}Mo is magic in neutron number and thus an imaginary strength somewhat smaller than the elemental value is to be expected.[26] The present real strengths are slightly larger (≈ 3%) than the values deduced by Rapaport et al.[23] from higher-energy measurements (i.e. $E_n > 7$ MeV). The small difference is easily attributable to uncertainties in the energy dependence of the real potential. The studies of ref. 23 imply a much smaller imaginary strength than deduced in the present work due to the choice of a large positive energy dependence in ref. 23. If a more conventional and modest energy dependence is assumed the discrepancy is alleviated. Generally, the success of the present (and similar) simple spherical OM's in describing the interaction of few-MeV neutrons with elemental molybdenum is encouraging, particularly in view of the apparent collective characteristics of some of the isotopes.[23,27]

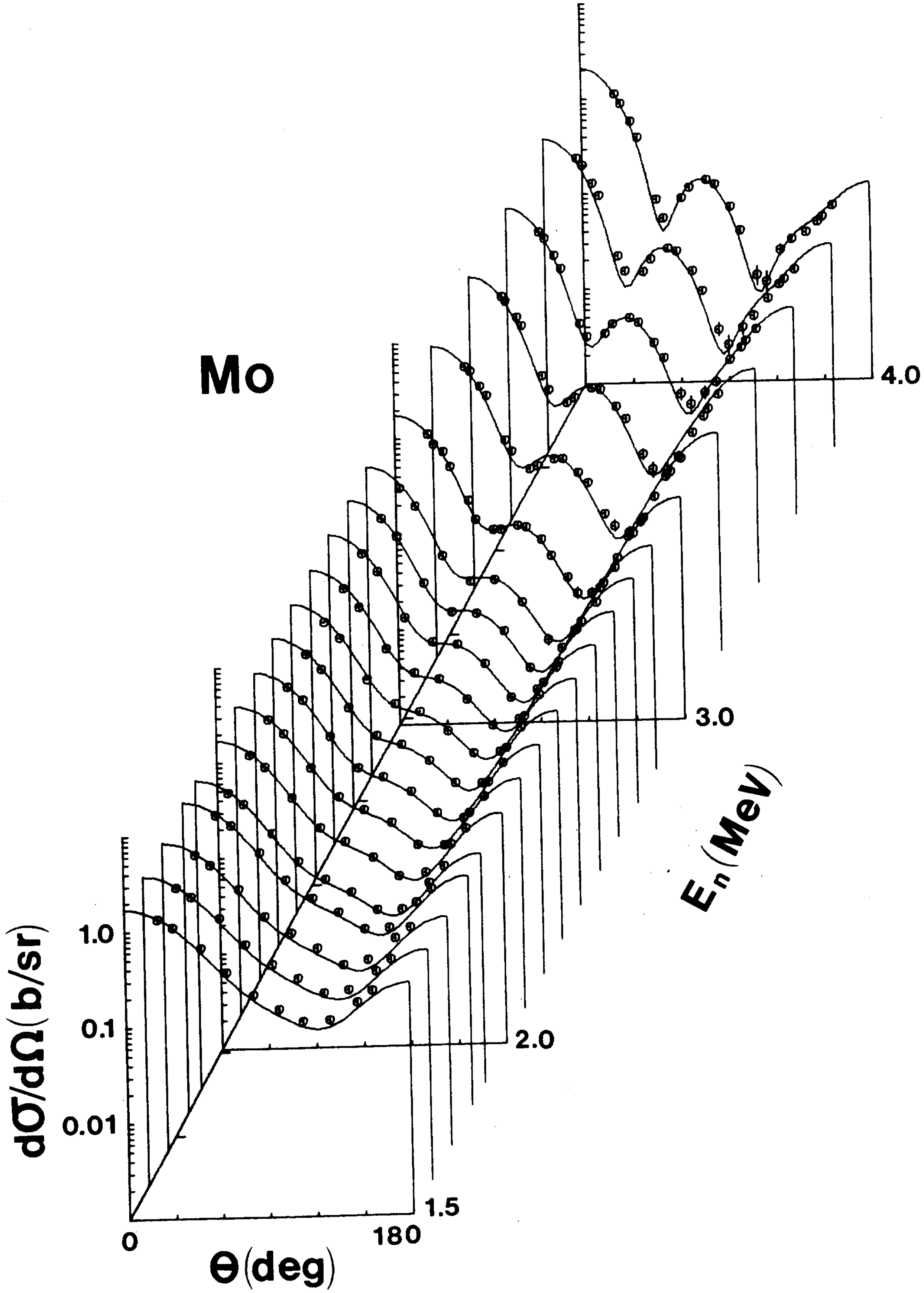

Fig. 4. Measured (data symbols) and Calculated (curves) Elemental Molybdenum Differential-Elastic-Scattering Cross Sections (in the lab. system).

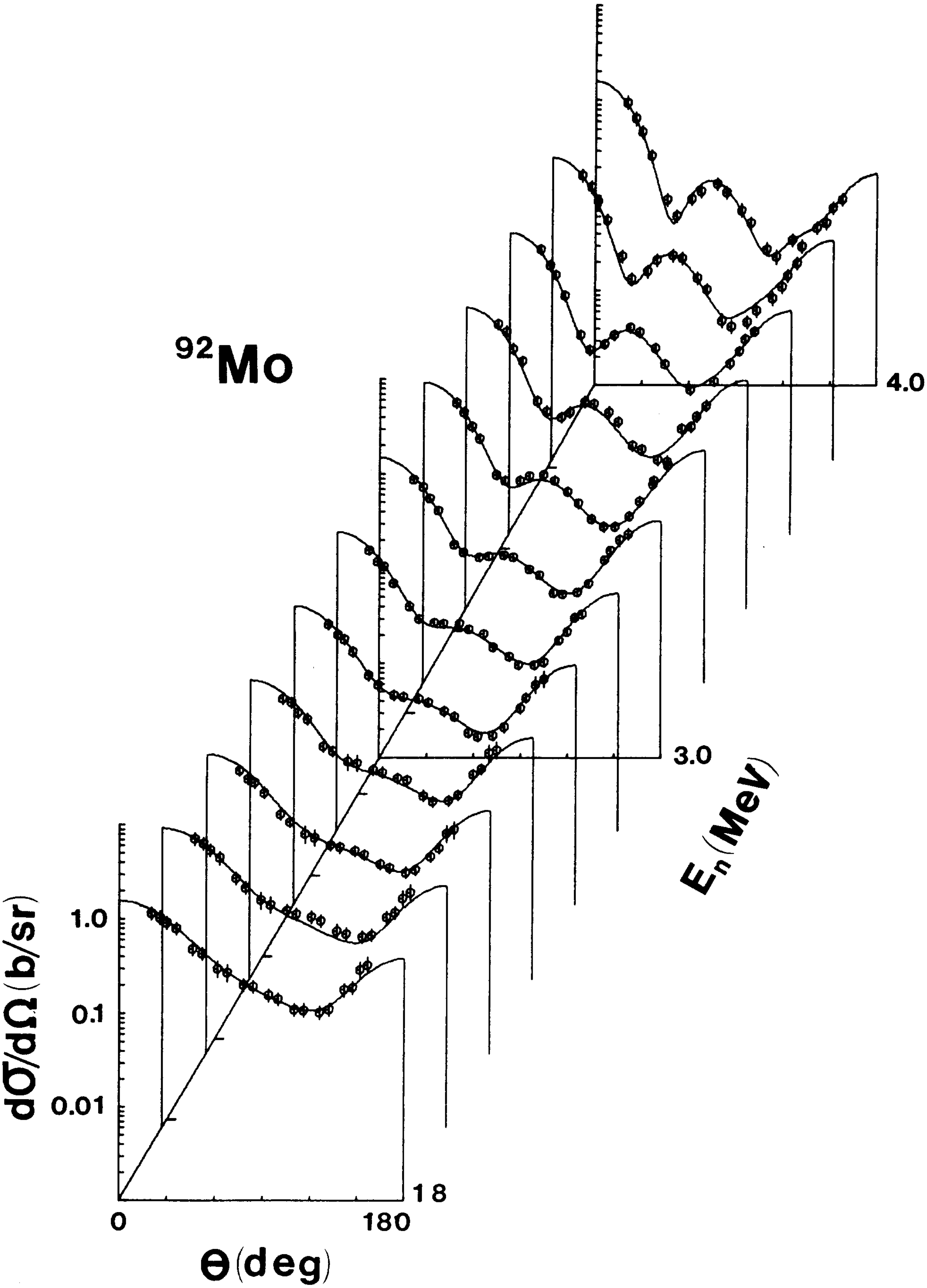

Fig. 5. Differential Elastic-Scattering Cross Sections of ^{92}Mo. The experimental values of ref. 17 are indicated by data symbols while curves indicate calculated results obtained with the potential of Table 2. (in lab. system).

V. COMPARISONS WITH ENDF/B-V

The present experimental results, and those of ref. 15, were compared with the relevant evaluated quantities given in ENDF/B-V (MAT-1321),[10] with the results indicated in Fig. 6. The measured and evaluated neutron total cross sections are generally in good agreement. There is a modest discrepancy near 1.0 MeV but only of about 5% magnitude. The measured angle-integrated elastic-scattering cross sections tend to be slightly larger than the evaluated quantities below about 3.0 MeV but the difference is generally within the 5% uncertainty of the present experimental values. The above consistency implies similar agreement between measured and evaluated nonelastic-scattering cross sections (i.e. between total inelastic-scattering cross sections). Detailed comparisons of discrete-inelastic-excitation cross sections were not attempted due to the complexity of levels, noted above.

VI. SUMMARY COMMENTS

The present measurements improve the definition of the neutron elastic-scattering cross sections of elemental molybdenum in the few-MeV region. The elastic-scattering cross sections were used to deduce a spherical optical-statistical model that provides a good description of the present experimental data, the reported neutron total cross sections,[15] and the elastic-scattering cross sections for the isotopes of molybdenum.[17] This model will be considered in the formulation of a "regional" model applicable to fission-product nuclides in this mass-energy region.[9] Eleven inelastically-scattered neutron groups were observed. Each of these appears to be a composited of contributions from a number of molybdenum isotopes. Broad-resolution lumped-level inelastic-scattering cross sections were determined for the most prominent of these excitations. The experimental results are in reasonably good agreement with the corresponding evaluated quantities of ENDF/B-V.[10]

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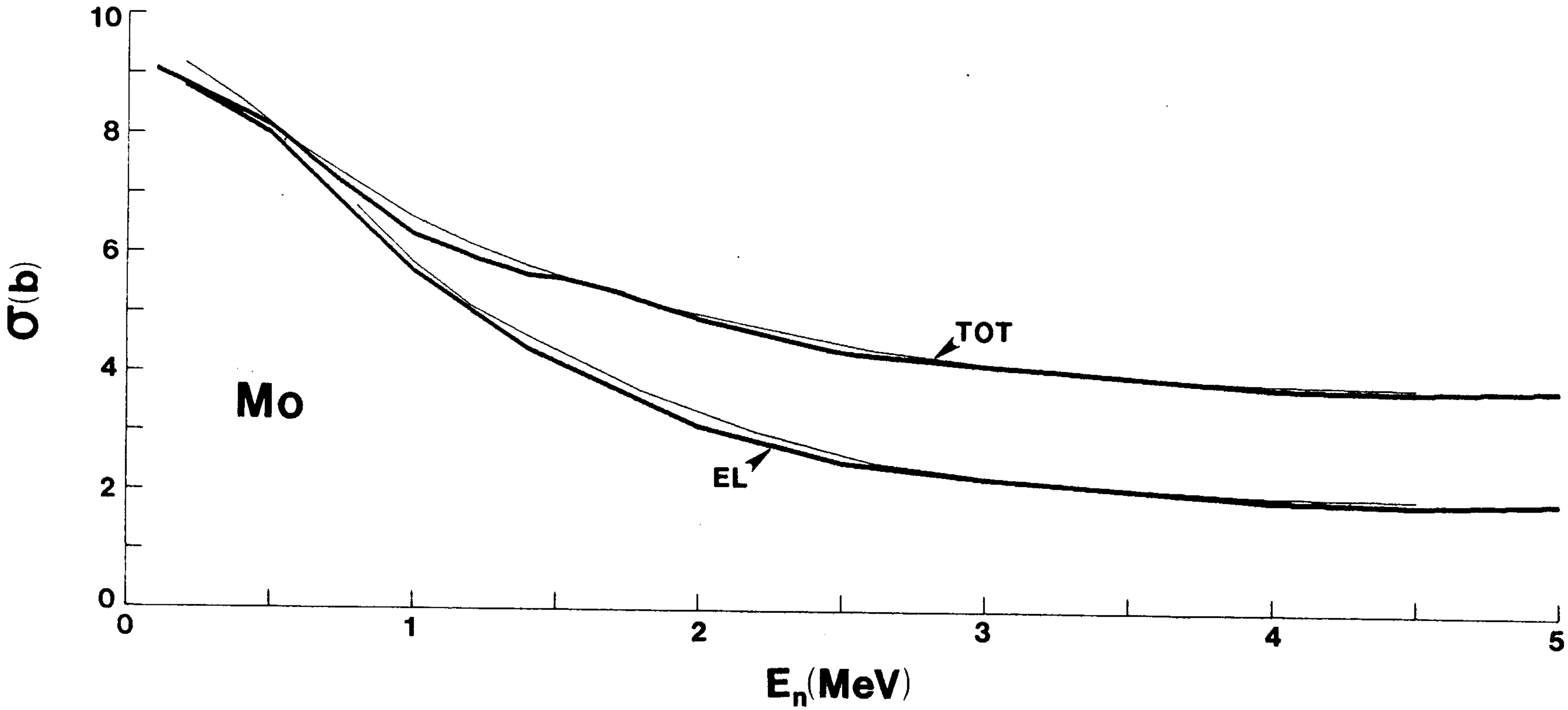

Fig. 6. Comparison of Measured and Evaluated Neutron Total and Angle-Integrated Elastic-Scattering Cross Sections of Elemental Molybdenum. The present experimental results and those of ref. 15 are indicated by "eyeguides" (light curves) and the ENDF/B-V[10] evaluation by the heavy curves.

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Table 1

Observed Excitation Energies

No	E_x (keV)[a]
1	789 ± 23[b]
2	1095 ± 23[b]
3	1240 ± 10[c]
4	1500 ± 34[b]
5	1617 ± 12[d]
6	1787[d]
7	1874[d]
8	1991[d]
9	2063 ± 24[d]
10	2296[d]
11	2569[d]
12	2802[d]

[a]Uncertainties defined as RMS deviation from the mean.

[b]Prominent excitation, cross sections determined.

[c]Probably entirely due to the second-neutron group from the source reaction.

[d]Tentative or marginal identification, cross sections not deduced.

Table 2

Elemental Molybdenum Optical-Model Parameters*

Real Potential[a]

Strength	V_o = 49.863	MeV
Radius[b]	R_v = 1.207	F
Diffuseness	A_v = 0.767	F
J_v/A[c] = 435.3 MeV × F^3		

Imaginary Potential[d]

Strength	W = 8.093	MeV
Radius	R_w = 1.399	F
Diffuseness	A_w = 0.438	F
J_w/A = 75.8 MeV × F^3		

[a]Saxon form; energy dependence of form $V = V_0 - 0.3\ E(\text{MeV})$ and spin-orbit potential of Thomas form with 6 MeV strength were assumed.

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

[c]Integral per nucleon.

[d]Energy independent Saxon-derivative form.

*Strengths obtained from a similar analysis of the isotopic results of ref. 17 are as follows.

Isotope	J_v/A (MeV × F^3)	J_w/A (MeV × F^3)
^{92}Mo	438	48
^{96}Mo	441	67
^{98}Mo	440	68
^{100}Mo	425	71