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ANL/NDM-66

Fast-Neutron Scattering Cross Sections of Elemental Silver

by

A.B. Smith and P.T. Guenther

May 1982

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

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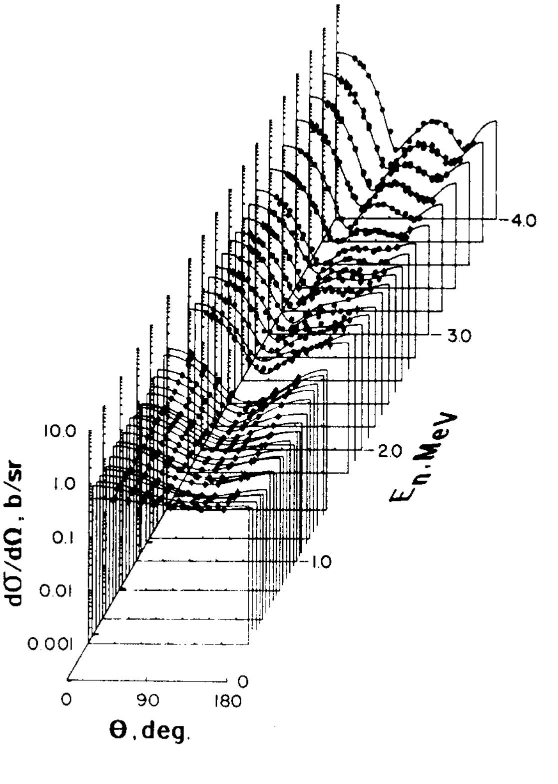

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*This work supported by the U. S. Department of Energy.

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ANL/NDM-71 Fast-neutron Total and Scattering Cross Sections of Elemental Palladium by Alan B. Smith, Peter T. Guenther and James F. Whalen (to be published).

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FAST-NEUTRON SCATTERING CROSS SECTIONS OF ELEMENTAL SILVER

by

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ABSTRACT

Differential neutron elastic- and inelastic-scattering cross sections of elemental silver are measured from 1.5 to 4.0 MeV at intervals of $\lesssim$ 200 keV and at 10 to 20 scattering angles distributed between 20 and 160 deg. Inelastically-scattered neutron groups are observed corresponding to the excitation of levels at; 328 ± 13, 419 ± 50, 748 ± 25, 908 ± 26, 1150 ± 38, 1286 ± 25, 1507 ± 20, 1623 ± 30, 1835 ± 20 and 1944 ± 26 keV. The experimental results are used to derive an optical-statistical model that provides a good description of the observed cross sections. The measured values are compared with corresponding quantities given in ENDF/B-V.

I. INTRODUCTION

This is the second of a series of reports dealing with the fast-neutron properties of fission-product nuclei in the region of light-mass fission product yields.[1] The general objective is the derivation of a model suitable for the calculation of unmeasurable neutronic properties of the light-mass fission products. The primary applied relevance is to Fast-Breeder Reactor (FBR) systems.

Elemental silver consists of two isotopes; ^{107}Ag (51%) and ^{109}Ag (49%).[2] Their fission-product yields can be significant. For example, in fission-neutron-induced fission of ^{239}Pu, the yields are ≈ 3.7% (^{107}Ag) and ≈ 1.6% (^{109}Ag). Both isotopes are in the first island of isomerism with p-1/2 ground states and low-lying (≈ 100 keV) 7/2 and 9/2+ isomeric levels.[3] The primary goal of the present measurements was the quantitative determination of the differential elastic-scattering cross sections, and from them the derivation of an appropriate optical-statistical model (OM). The measurements extended over a region where the model is sensitive to compound-nucleus (CN) contributions. A secondary goal was the determination of differential inelastic-scattering cross sections. The latter results are primarily of applied interest as the intentionally broad incident-energy spreads employed in the measurements precluded detailed resolution of excited-level structure.

Subsequent portions of this report deal with: i) a very brief outline of the experimental methods (Sec. II), ii) the experimental results (Sec. III), the derivation of an OM (Sec. IV), iii) and some comparisons with ENDF/B-V (Sec. V).

II. OUTLINE OF EXPERIMENTAL METHODS

All the measurements were made at the Argonne National Laboratory Fast-neutron Generator using the ten-angle time-of-flight apparatus.[4] The neutron source was the ^{7}Li(p,n)^{7}Be reaction.[5] The measurement sample was a cylinder 2 cm in diameter and 2 cm long, fabricated from high purity elemental silver. The average incident-neutron energies were known to ≈ 10 keV and the incident-neutron energy spreads were ≈ 70 to 100 keV. The ten scattered-neutron flight paths were ≈ 5.4 m long. Ten proton-recoil scintillation detectors were used to detect the scattered neutrons and an eleventh detector monitored the source intensity. The relative energy-dependent responses of the detectors were determined by observation of the fission neutrons emitted by the spontaneous fission of ^{252}Cf.[6] These relative responses were normalized absolutely relative to the neutron total cross sections of carbon[7] as described in Ref. 8. The resulting differential-scattering cross sections were corrected for angular-resolution, incident-neutron-attentuation and multiple-event effects as described in Ref. 9. The statistical uncertainties of the measured differential elastic-scattering cross sections were $\lesssim$ 2% except near the extreme minima of the distributions where they were larger. The statistical uncertainties of the inelastic-scattering results varied from ≈ 10% to 30% depending upon the particular inelastic-neutron group. Uncertainties associated with detector-calibration procedures were $\lesssim$ 3%. Neutron scattering angles were known to $\lesssim$ 0.75 degree. Correction procedures introduced an additional $\lesssim$ 1% uncertainty, again excepting the extreme minimia of the elastic distributions where they were larger. Thus the overall uncertainties for differential-elastic scattering cross sections were generally $\lesssim$ 5%, and for differential-inelastic scattering, $\approx$ 10% to 30%.

III. EXPERIMENTAL RESULTS[a]

A. Neutron-Elastic-Scattering Cross Sections

The differential-elastic-scattering measurements were made at incident energies extending from 1.5 to 4.0 MeV. Below 3.0 MeV the measurements were made at intervals of $\approx$ 50 keV (i.e., at intervals smaller than the incident-energy resolution) and at ten scattering angles distributed between $\approx$ 20 and 160 degrees. The above cited broad resolutions were intentionally used in order to enhance the statistical accuracies and to average possible cross-section fluctuations. These broad resolutions precluded the separation of the elastic- and first-two-inelastic-scattered neutron groups corresponding to similar levels in ^{107}Ag and ^{109}Ag ($E_x \cong$ 0.0, $\approx$ 0.09 and $\approx$ 0.125 keV). Thus, all the "elastic-scattering" results obtained in the present work are inclusive of two small inelastic-scattering components. The latter are dealt with in the interpretation as described below. The possible effect of fluctuations was further reduced by averaging differential cross sections obtained at adjacent energies up to incident energies of 3.0 MeV. Above 3.0 MeV the measurements were made at 200 keV intervals and at twenty scattering angles. At these higher energies the fluctuations should be neglegible but the angular dependences of the cross sections are strong thus the additional angular detail was desirable.

The measured "elastic-scattering" results are illustrated in Fig. 1. In order to obtain the angle-integrated "elastic-scattering" cross sections, the measured values were least-square fitted with 6th-order Legendre-Polynomial series. The results of this fitting procedure are illustrated by the curves of Fig. 1 and the corresponding angle-integrated cross-section values are shown in Fig. 2. Of course, these angle-integrated results also include the two small inelastic-scattering components noted above. The uncertainties associated with the angle-integrated results are $\lesssim$ 5%. The present "elastic-scattering" values reasonably extrapolate to the lower-energy results of Ref. 10, as illustrated in Fig. 2. They are also consistent with the ^{107}Ag isotopic results of Ref. 11. The latter measurements fully resolved the elastic scattering and consequently the extreme minima of the distributions are slightly smaller than those of the present work at the lower energies where compound-nucleus cross sections are large. In addition, the ^{107}Ag and elemental level structures differ; resulting in different compound elastic-scattering (CE) contributions and thus in variations between elemental and isotopic scattering cross sections.

B. Neutron Inelastic-Scattering Cross Sections

The primary objective of the present measurement was the determination of energy-averaged elastic scattering cross sections and the energy resolution

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a) Numerical values for all experimental results reported herein have been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory.

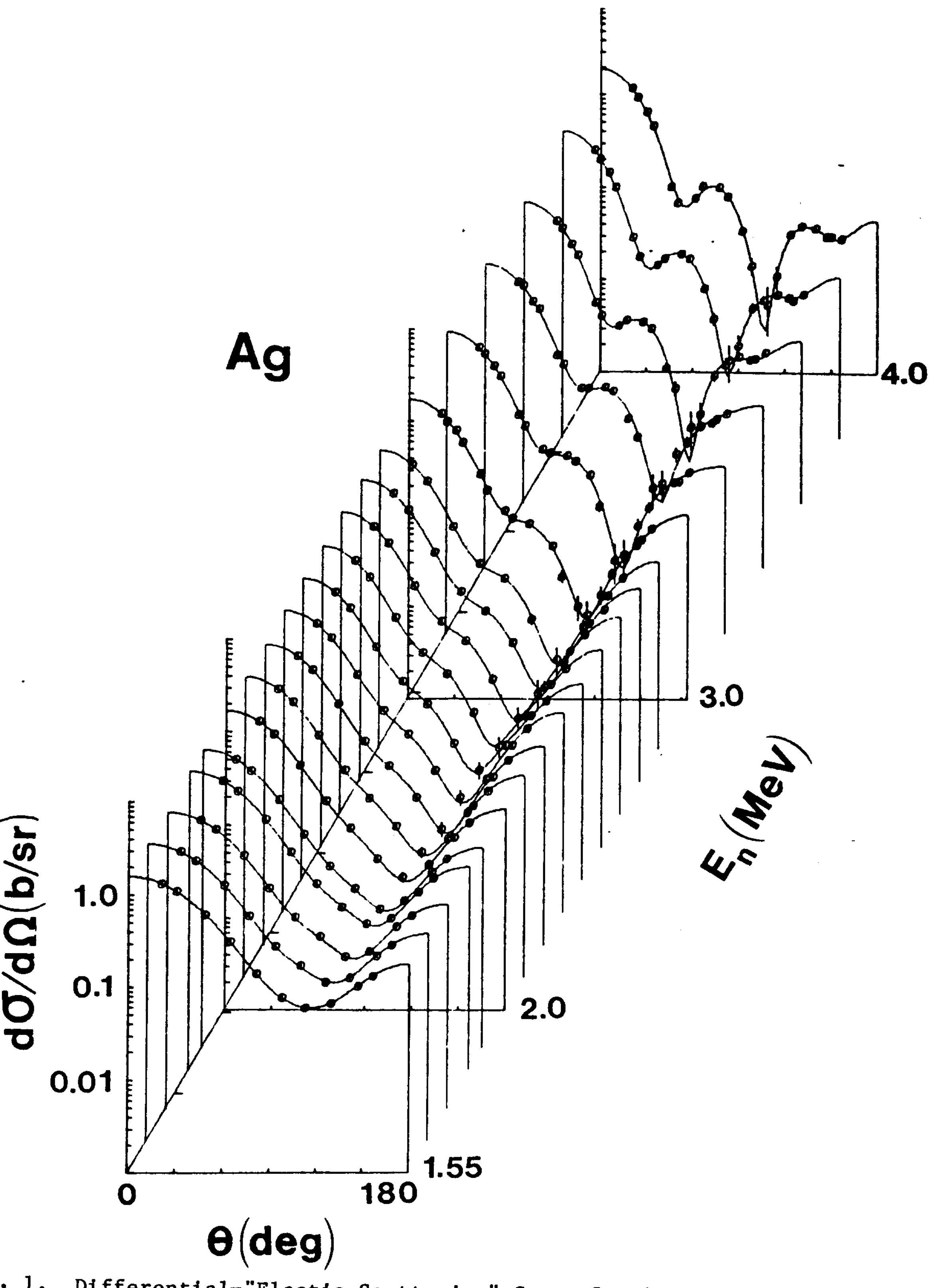

Fig. 1. Differential-"Elastic-Scattering" Cross Sections of Elemental Silver. The present measured values are indicated by data symbols. Curves denote the results of fitting Legendre-Polynomial series to the measured values. Angle is expressed in the laboratory system.

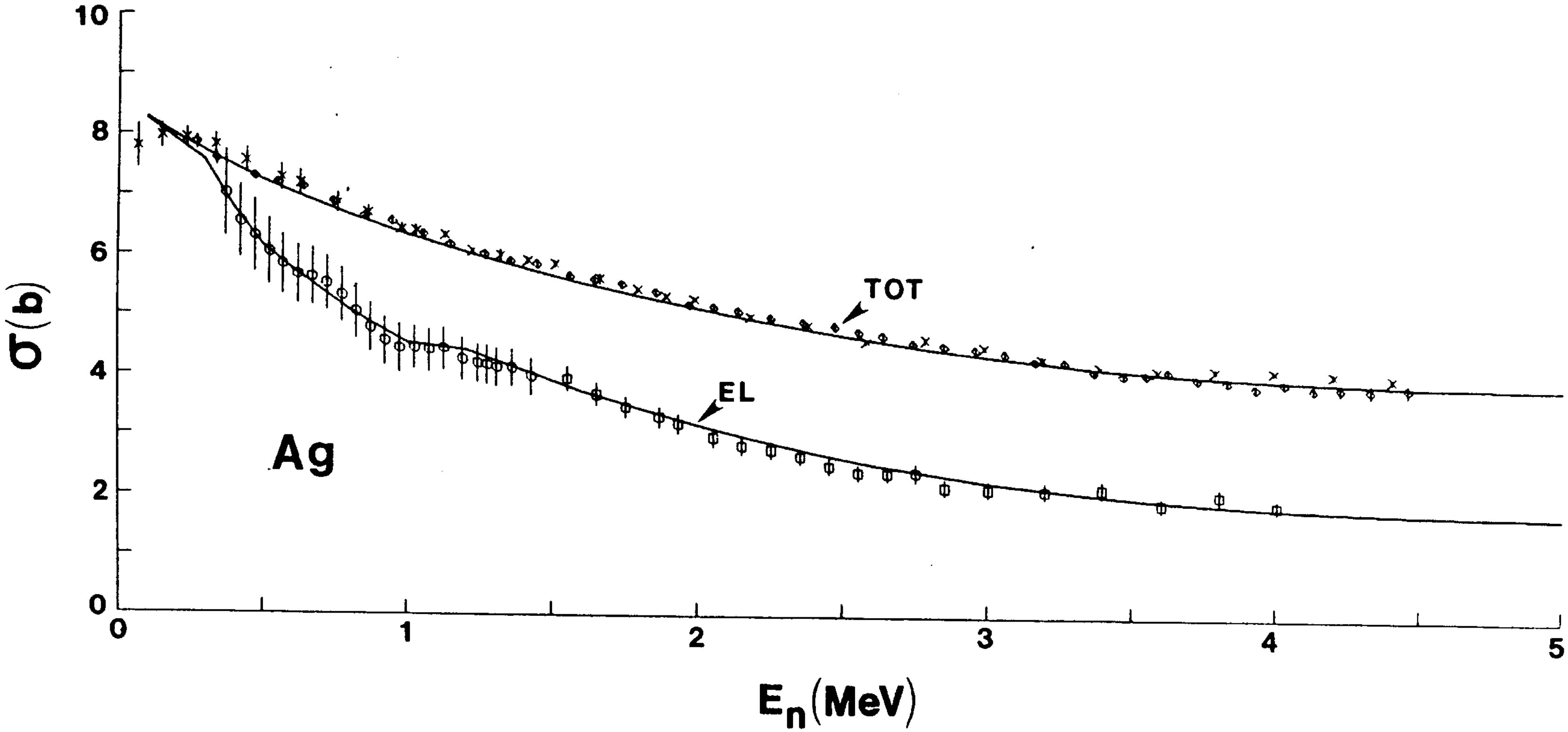

Fig. 2. Neutron Total and "Elastic-Scattering" Cross Sections of Elemental Silver. The present experimental results are indicated by □ , those of Ref. 10 by O, those of Ref. 11 (^{107}Ag) by ◇, and those of Ref. 12 by X. Curves indicate the results of model calcu-lations as described in the text.

was chosen accordingly. As a consequence of this and of the complex level structure of elemental silver the inelastic scattering cross sections were not well resolved. However, ten distinct inelastically-scattered neutron groups were observed that could be generally attributed to the excitation of two or more levels in ^{107}Ag and/or ^{109}Ag. The correlation of the observed neutron groups with reported levels in the two isotopes is outlined in Table 1.[2] The excitation energies derived from the measurements are averages of a number of observed values with the respective uncertainties defined as the RMS deviations from the simple averages.

The angle-integrated cross sections were determined by least-square fitting the measured differential values with low-order Legendre-Polynomial series (e.g., $\lesssim P_2$ as the observed differential-cross-section anisotropics were small). The uncertainties associated with the angle-integrated inelastic values vary from $\approx$ 10% to 30% depending upon the particular measurements. The contributions to the uncertainties were as outlined above with an additional factor due to necessary corrections for the second-neutron group from the source reaction. The resulting inelastic-cross-section values are summarized in Fig. 3. As noted above, the measurements intentionally did not resolve the first two inelastic-neutron groups ($E_x \approx$ 90 keV(7/2+) and $\approx$ 130 keV (9/2+)). Excitations of these two levels are indicated in Fig. 3, based upon previously reported work from this Laboratory.[10,11] Cross sections for the excitation of the 328 keV (3/2-) level were determined at lower incident energies. As the energy increased this level was observed as a composite excitation with the 419 keV (5/2-) level due to the broad incident-neutron resolutions employed in the measurements. Furthermore, excitations in the region of 400-500 keV were particularly complicated by the presence of the elastically-scattered second neutron group from the source reaction. The appropriate corrections for this second-group perturbation considerably increased the uncertainty in this case. Cross sections corresponding to the excitation of a 748 keV level were attributed to contributions from ^{107}Ag and ^{109}Ag as outlined in Table 1. Cross sections for the remaining seven groups also appear to be due to levels in both ^{107}Ag and ^{109}Ag (see Table 1). These correlations are complex and, for $E_x \gtrsim$ 1300 keV, the reported levels of the two isotopes become increasingly uncertain.[2] Generally the present cross sections are consistent with the lower-energy elemental results of Ref. 10 and with the ^{107}Ag isotopic results of Ref. 11 where ^{109}Ag contributions do not significantly distort the comparisons. Moreover, the sum of the "eye-guides" of Fig. 3 are in good agreement with the non-elastic cross sections implied by the present elastic-scattering results and the neutron total cross sections of Ref. 12.

IV. INTERPRETATION AND DISCUSSION

It was assumed that the present results could be reasonably described by a spherical optical-statistical model (OM).[13,14] The low-lying levels of the two isotopes are similar but those of ^{109}Ag are better known as the energy increases.[2] Therefore this interpretation was based upon the discrete levels of ^{109}Ag, as given in Ref. 2, to excitations of 1260 keV. Higher-energy levels were represented using the statistical parameterization of Gilbert and Cameron.[15] The elemental mass was defined as $A \equiv 108$. The

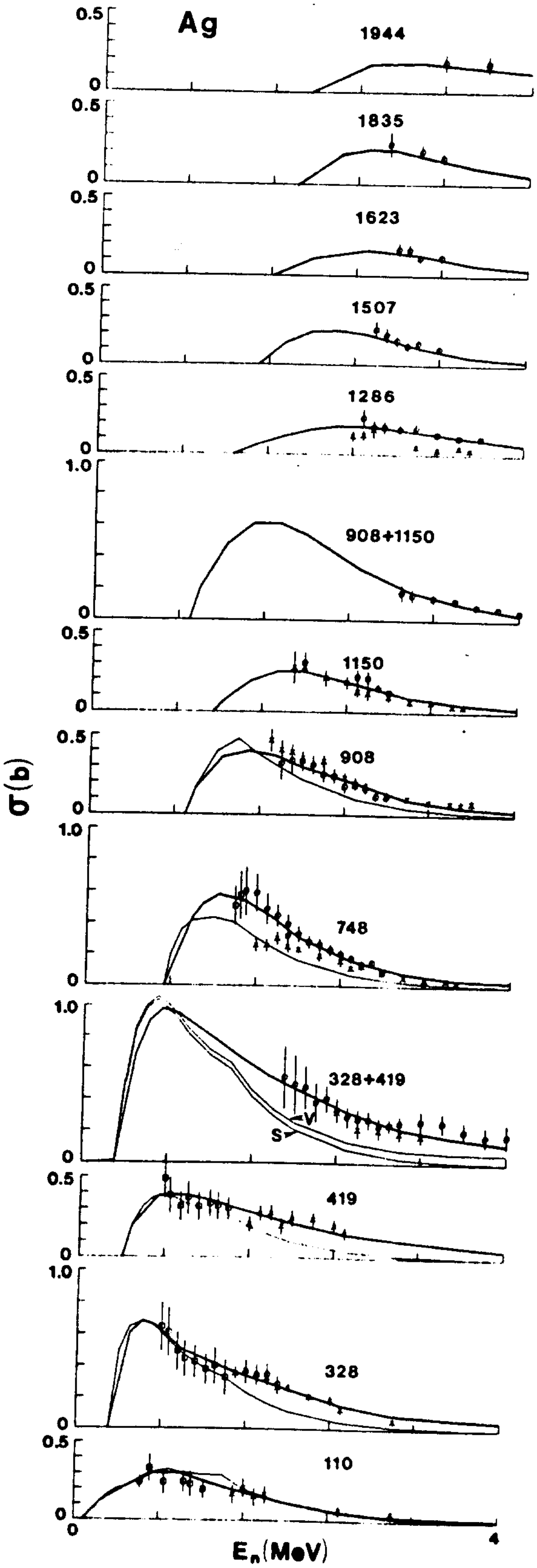

Fig. 3. Neutron Inelastic-Scattering Cross Sections of Elemental Silver. Measured values are indicated by data symbols as follows; O = present work, □ = Ref. 10, and X = Ref. 11. Heavy curves are "eyeguides", the light curves indicate the results of calculations as discussed in the text. Observed excitation energies are given in keV.

calculations used the OM code ABAREX with resonance fluctuation and correlation corrections as described by Moldauer.[16,17] The OM parameters were derived by concurrently chi-square fitting all of the measured differential-elastic-scattering cross sections of Fig. 1. The fitting procedure combined the first two inelastic-neutron groups ($E_x \approx 0.09$ and 0.125 keV) with the elastic-scattering component in correspondence with the measured values. The fitting procedure simultaneously considered the six parameters; real and imaginary strengths, radii and diffusenesses. The resulting OM parameters are given in Table 2. These parameters are relatively conventional. The real strength (measured in integral-per-nucleon J_V/A or Vr^2) is similar to that reported in the literature.[11,18] The imaginary strength (J_W/A or Wa) tends to be somewhat larger than that frequently reported.

The parameters of Table 2 provide a generally good description of the measured differential-"elastic-scattering" cross sections as illustrated in Fig. 4. There are small systematic differences between the measured and calculated values near the extreme minima of the distributions from $\approx$ 2 to 3 MeV. This is a region sensitive to compound-elastic-scattering (CE) which here is largely governed by channel competition from the statistically-based levels. The latter are not well defined and may vary from nucleus to nucleus, particularly at these low energies. The measured angle-integrated elastic-scattering cross sections are described well by the calculations as illustrated in Fig. 2. The neutron total cross sections of Ref. 12 are also described well by the calculations. At $\approx$ 4.0 MeV the elemental total cross sections of Ref. 12 are $\approx$ 2% to 3% larger than the ^{107}Ag values of Ref. 11. Calculations indicate that the nuclear size effect accounts for $\approx$ 1% of this difference, leaving a $\approx$ 1% to 2% difference which is consistent with the respective experimental uncertainties.

Calculated inelastic-scattering cross sections are compared with measured values in Fig. 3. The agreement is good at the lower energies where the excitation of discrete levels governs the processes. However, as the energy increases and the channel competition becomes dominated by statistical level distributions, the calculated values become markedly smaller than the measured quantities; particularly for the excitations of the 328 keV (3/2-) and 419 keV (5/2-) levels. This suggests that the statistical level parameters result in too much channel competition. The discrepancy can be reduced by adjusting the level parameters without a large effect on the elastic-scattering process as the CE component is already small. Such pragmatic parameter adjustment was not pursued. It has been suggested that both silver isotopes are vibrators[19] with the first 3/2- and 5/2- levels coupled to the ground state in a direct-vibrational excitation. The magnitude of such a direct-vibrational excitation was estimated using a coupled-channels calculation assuming $\beta_2 = 0.15$.[20] The vibrational coupling results ("V") are compared with the spherical results ("S") in Fig. 3. The enhancement of the inelastic cross sections due to the direct process is significant and will increase with β_2. However, all the calculated inelastic-scattering cross sections remain smaller than the measured values. The introduction of vibrational coupling will effect the choice of OM parameters to some extent at the present energies. Comprehensive fitting, using the vibrational model was not attempted since the spirit of the interpretation was a simple spherical OM. Comprehensive fitting with a

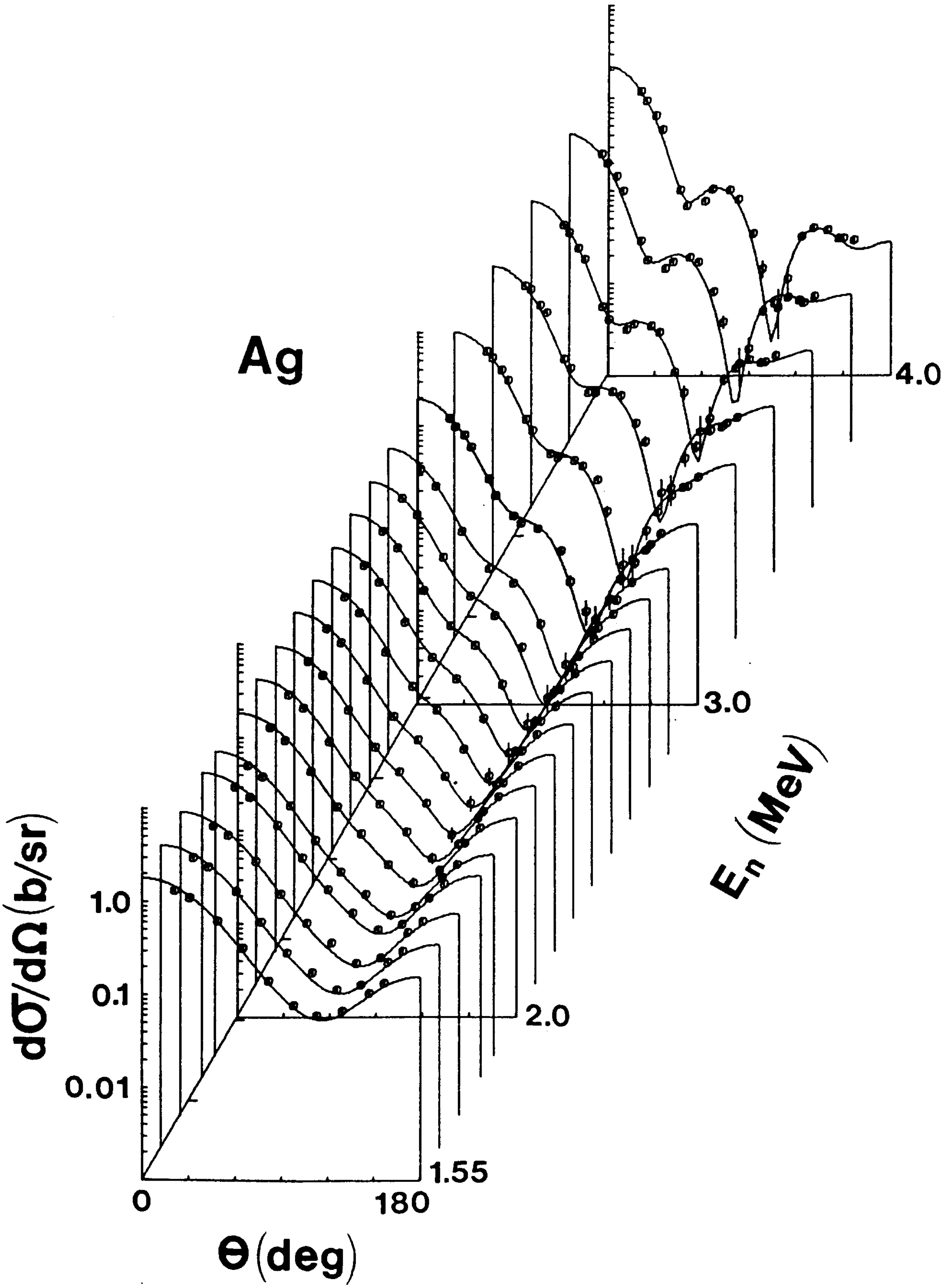

Fig. 4. Comparison of Measured and Calculated Differential-Elastic-Scattering Cross Sections of Elemental Silver. The measured values are indicated by data symbols and the results of model calculations by curves.

vibrational model is costly in computing time, and the major calculational uncertainty would probably remain the statistical-level parameters.

V. COMPARISONS WITH ENDF/B-V

The ENDF/B-V evaluated data file [21] contains isotopic ^{107}Ag and ^{109}Ag data sets. These were combined to obtain an elemental file for comparison with the present measurements. Figure 5 compares measured and evaluated neutron total[21] and elastic-scattering cross sections (small corrections have been made for inelastic contributions to the measured values as necessary). Near 4.0 MeV the agreement is good for both cross sections. However, as the energy decreases the evaluated results become increasingly larger than the measured quantities, the difference amounting to ≈ 8% at several hundred keV. That is a significant discrepancy, particularly with respect to the total cross section which forms the envelope of an evaluated data set. Moreover, the discrepancy is largest at the low energies where the neutron capture cross section is important. The non-elastic-scattering cross section derived from the present measurements and the total cross section of Ref. 12 is in reasonably good agreement with the evaluated total inelastic-scattering cross section. There is a similar reasonable agreement at low energies between the evaluated individual inelastic-excitation cross sections and the measured values of Refs. 10 and 11. The agreement may be fortuitous in view of the above noted discrepancies between measured and evaluated neutron total and elastic-scattering cross sections.

VI. SUMMARY COMMENT

The present measurements give new and detailed definition to neutron elastic scattering from elemental silver and improve the knowledge of inelastic scattering over the few-MeV region. Combined with recently measured neutron total cross sections and previously reported scattering cross sections from this Laboratory[10-12], a reasonably comprehensive experimental understanding of the neutron interaction with elemental silver is obtained from a few-hundred keV to above 4 MeV. The measured "elastic-scattering" results form a data base from which a spherical OM was derived. That OM is consistent with a general OM applicable to the light-mass fission products to be reported elsewhere.[22] In addition, details of the experimental interpretation suggest that direct-vibrational processes may play a part in the neutron interaction with silver in the several-MeV region. The present experimental results are reasonably consistent with the evaluated quantities of ENDF/B-V[21] at energies of 4 to 5 MeV. At lower energies there are discrepancies between measured and evaluated results with the measured neutron total[12] and elastic-scattering cross sections becoming increasingly smaller than the evaluated quantities as the energy decreases.

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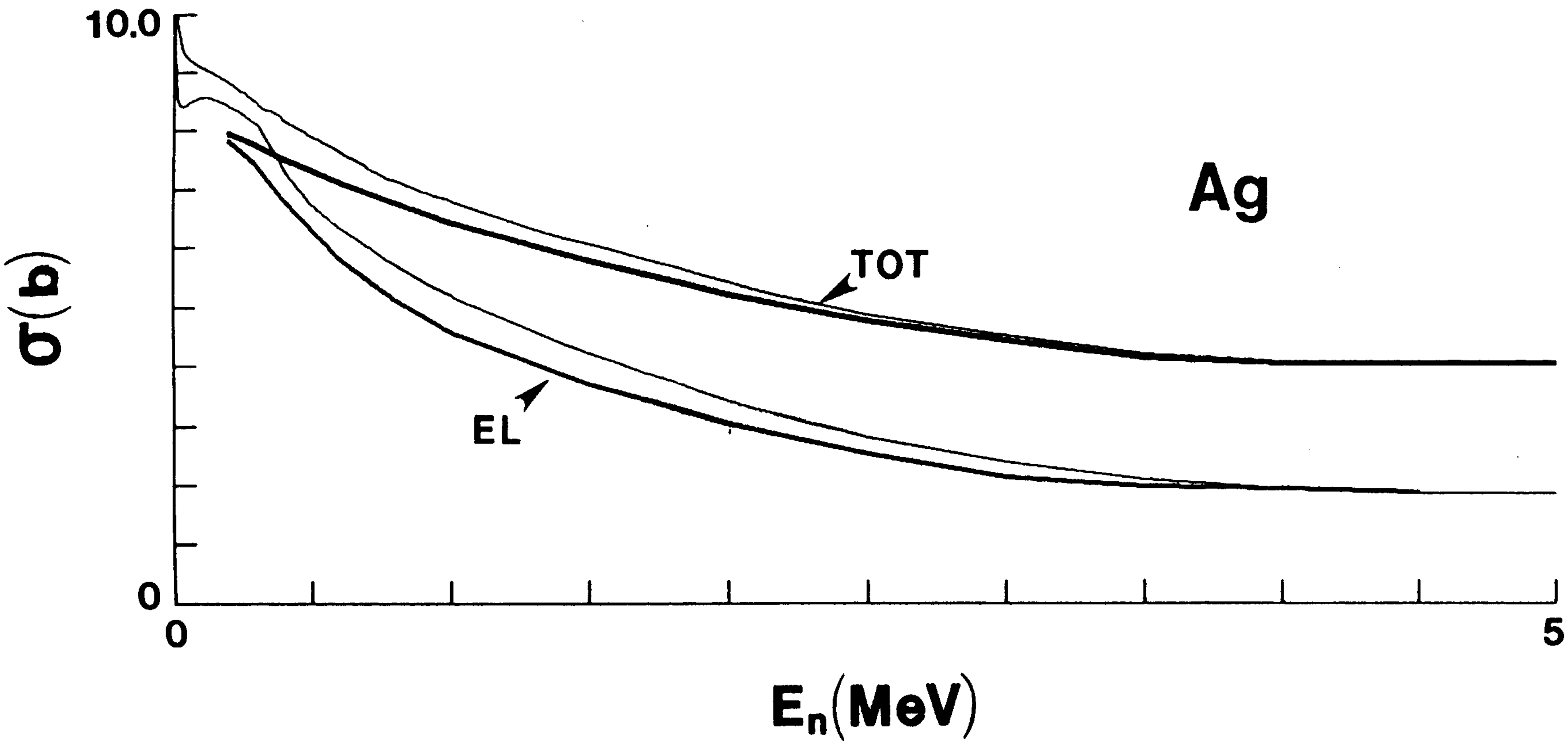

Fig. 5. Comparison of Measured and Evaluated Neutron Total and Elastic Scattering Cross Sections of Elemental Silver. The light curves were deduced from ENDF/B-V.[21] The heavy curves are eyeguides constructed through the neutron total cross sections of Ref. 12 and the elastic-scattering results of the present work.

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TABLE 1. Observed Excitation Energies[a]

		Attributed Components[b]	
No.	E_x(exp)	^{107}Ag	^{109}Ag
1	328 ± 13[c]	325(3/2-)	311(3/2-)
2	419 ± 50[d]	423(5/2-)	415(5/2-)
3	748 ± 25	787(3/2-)	702(3/2-) 706(3/2+) 731(3/2+)
4	908 ± 26	922(5/2+) 950(5/2-) 973(5/2-)	863(5/2-) 869(5/2+) 910(7/2+) 912(7/2-)
5	1150 ± 38	1050(?) 1143(5/2-) 1160(?)	1091(9/2-)
6	1286 ± 25	1222(5/2+) 1250(?) 1259(3/2+) 1325(?)	1200(?) 1260(1/2-) 1324(3/2-)
7	1507 ± 20	1465(3/2-) 1482(?)	1430(1/2-) 1490(?) 1524(3/2-)
8	1623 ± 30	1600(?) 1613(1/2-) 1660(1/2+) 1670(?)	1573(?) 1615(1/2-) 1653(1/2-) 1688(?)
9	1835 ± 20	-	-
10	1944 ± 26	-	-

[a]All energies in keV.

[b]Energies and Jπ values taken from Ref. 2.

[c]Uncertainties are RMS deviations from simple mean. Values of E_x are averages not necessarily corresponding to scattered-neutron resolutions.

[d]Energies uncertain due to presence of the second neutron-group from the source reaction.

Table 2. Optical-Model Parameters[a]

Real Potential[b]			
V_o[c]	=	48.25	MeV
r[d]	=	1.249	F
a	=	0.603	F
J_V/A	=	433.7	MeV-F^3
$V_o r^2$	=	75.27	MeV-F^2
Imaginary Potential[e]			
W	=	8.50	MeV
r[d]	=	1.270	F
a	=	0.575	F
J_W/A	=	85.7	MeV-F^3
Wa	=	4.89	MeV-F

[a]Also spin-orbit potential of Thomas form[13] with 6 MeV depth.

[b]Saxon form.[13]

[c]Energy dependence of form $V = V_o - 0.3 \cdot E$ (MeV).

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

[e]Saxon-derivative form.[13].