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NEUTRON TOTAL AND SCATTERING CROSS SECTIONS OF ELEMENTAL ANTIMONY*

by

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November 1982

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Table of Contents

Page

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by

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ABSTRACT

Neutron total cross sections are measured from 0.8 to 4.5 MeV with broad resolutions. Differential-neutron-elastic-scattering cross sections are measured from 1.5 to 4.0 MeV at intervals of 50 to 200 keV and at scattering angles distributed between 20 and 160 degrees. Lumped-level neutron-inelastic-scattering cross sections are measured over the same angular and energy range. The experimental results are discussed in terms of an optical-statistical model and are compared with respective values given in ENDF/B-V.

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I. INTRODUCTION

This study was undertaken as part of a series of experimental investigations of the fast-neutron interaction with light-mass fission products. Elemental antimony consists of two essentially equally-abundant isotopes: ^{121}Sb(57.3%) and ^{123}Sb(42.7%). Both have small fission-product yields, typically a few times 10^{-2}%. Thus the isotopes of antimony are not fission products of direct applied interest. However, the element is near the shell closure at Z=50 and at the upper-mass extreme of the light-mass fission yields. Thus the fast-neutron interaction with antimony is of interest in the context of the systematic behavior of the fast-neutron interaction with light-mass fission products. In particular, antimony is a worthwhile reference point for determining model parameters useful for extrapolating observed neutron processes into experimentally inaccessible fission-product regions. The objectives of the present work were the provision of an experimental foundation and the subsequent development of parameters for a relevant optical-statistical model (OM). This and similar models contributed to the formulation of a "regional" OM generally applicable to light-mass fission products, as described elsewhere.[1] Subsequent portions of these remarks deal with the experimental results, the derivation of the model, and comparisons of the present results with values given in ENDF/B-V.[2]

II. EXPERIMENTAL METHODS

The experimental samples were solid metal cylinders of chemically pure elemental antimony. Those used in the neutron-total-cross-section measurements were 2.5 cm in diameter and 1.25 cm long. They were stacked to obtain neutron transmissions in the range 40% to 60%. The scattering sample was a cylinder 2 cm in diameter and 2 cm long. Sample densities were determined by precise weight and dimension measurements.

The neutron total cross sections were determined from the observed neutron transmissions through the measurement samples in the conventional manner.[3] 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 samples were placed $\approx$ 1 m from the source at a zero-degree reaction angle. The measurement samples and void positions were alternated in the neutron beam $\approx$ 24 times a minute. Neutrons were detected with a proton-recoil scintillator placed 4 to 6 m from the source. Conventional time-of-flight techniques were used to suppress background effects and to select the primary neutron group from the source reaction. In-scattering effects were negligible. A reference pulser was introduced into the measurement system to assure proper corrections for dead-time effects. Neutron total cross sections of carbon were concurrently determined in order to verify the performance of the apparatus.[4] The measurement method and apparatus were identical to those described in detail in ref. 5.

The neutron-scattering measurements utilized the Argonne National Laboratory 10-angle time-of-flight apparatus.[6] The neutron source was, again, the

^{7}Li(p;n)^{7}Be reaction. The neutron detectors were placed at the ends of $\approx$ 5.4 m flight paths distributed over the angular range 20 to 160 degrees. The relative angular scale was determined to within ± 0.2 degrees and the absolute setting of the angular system to within ± 0.7 degrees. Below 3.0 MeV the measurements were made at ten angles; at higher energies twenty angles were used. Relative neutron-detector sensitivities were determined by the observation of neutrons emitted from the spontaneous fission of ^{252}Cf.[7] The absolute normalization of these detector efficiencies was determined relative to the neutron total cross sections of carbon[4] in the manner described in ref. 8. This normalization method implies that the antimony scattering cross sections were determined relative to the neutron total cross sections of carbon. All of the measured differential-scattering cross sections were corrected for multiple-event, beam-attenuation and angular-resolution effects as described in ref. 9. The latter reference also contains a detailed description of the measurement apparatus and its applications.

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

The neutron total-cross-section measurements were made with incident-neutron energy resolutions of 30 to 50 keV from $\approx$ 0.8 to 4.5 MeV at intervals of $\approx$ 50 keV. Several sets of data, covering the entire energy range, were obtained. These sets were averaged over 100 keV intervals to obtain the experimental results shown in Fig. 1. The statistical uncertainties of the averaged values are $\approx$ 1%. The results were extended to lower energies (as shown in Fig. 1) using a 50 keV average of the recent experimental values of Poenitz et al.[10] Self-shielding effects were estimated using the methods of ref. 10 and they were found to be negligible in the energy range of the present measurements. The prior neutron-total-cross-section data base should be reasonably summarized by ENDF/B-V[2]. Comparisons with that evaluated data set are discussed below.

B. Neutron Scattering Cross Section

The differential scattering measurements were made from $\approx$ 1.5 to 4.0 MeV in steps of $\approx$ 50 keV below 3.0 MeV and steps of $\approx$ 200 keV at higher energies. Energy-adjacent distributions were averaged below 3.0 MeV. The incident-neutron energy spreads were 50 to 70 keV. These relatively large values were chosen so as to average possible energy-dependent fluctuations, enhance statistical accuracies and remove ambiguities due to experimental resolution. The latter were a concern with the elemental antimony targets. ^{121}Sb has a 5/2+ ground state and a 7/2+ first-excited level at 37 keV while ^{123}Sb has a 7/2+ ground state and a 5/2+ first-excited level at 160 keV.[12] The complete resolution of these components throughout

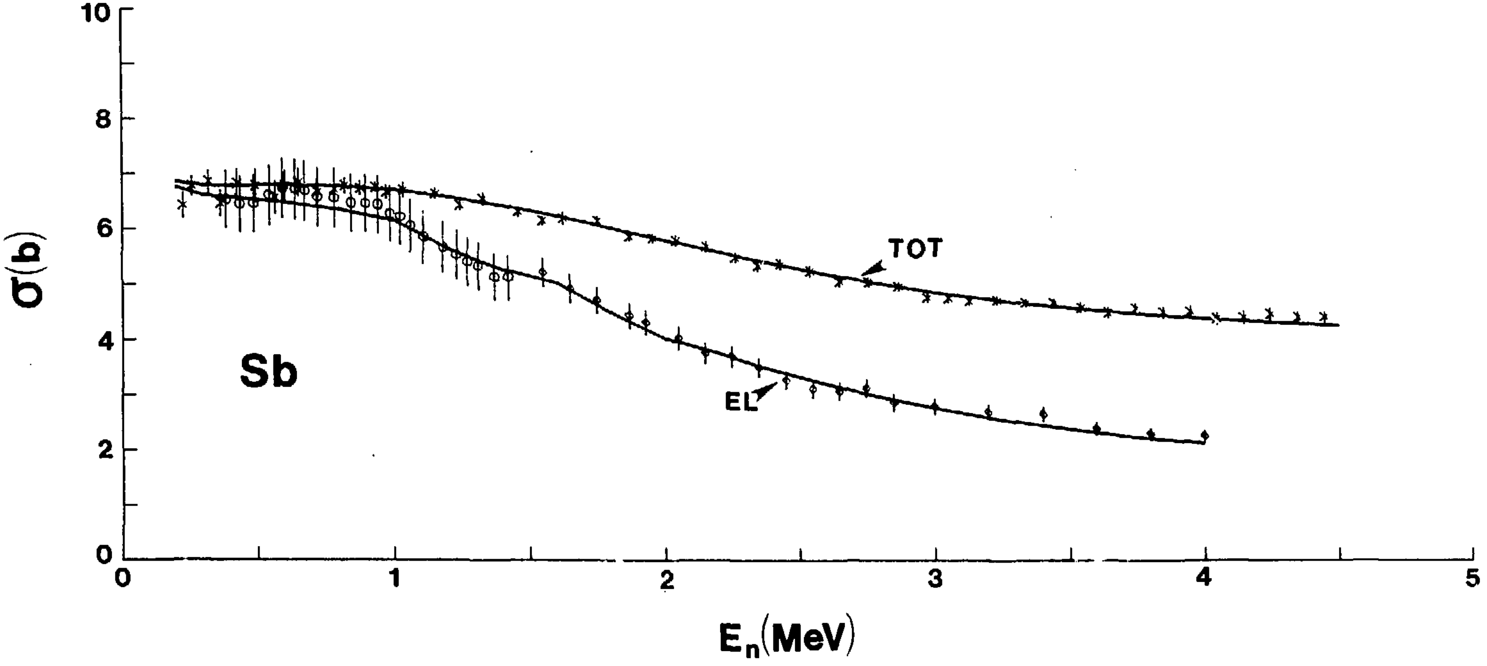

Fig. 1. Neutron Total and Elastic-Scattering Cross Sections of Elemental Antimony. The present experimental results are indicated by X and ◇ (total cross sections extended below 0.8 MeV using 50 keV averages of the recent results of ref. 10). The lower-energy elastic-scattering values of ref. 11 are indicated by ○. Curves denote the results of model calculations as described in the text.

the measured energy range would be exceedingly tedious with possibly uncertain results. Therefore, the measurements intentionally included inelastically scattered neutrons due to the excitation of both first-excited levels with the elastically-scattered component. This observational reality was treated in the interpretation, as discussed below.

The differential-elastic-scattering results are summarized in Fig. 2. The distributions behave in an energy-smooth manner. The statistical uncertainties of the individual experimental values were $\lesssim$ 1%. The uncertainties associated with the detector calibrations were $\approx$ 3%. Correction procedures introduced an additional $\lesssim$ 1% uncertainty. Thus the overall differential-elastic-scattering uncertainties were $\approx$ 5%. Near the extreme minima of the distributions the statistical uncertainties associated with both the experimental measurements and the correction procedures were larger. The angle-integrated elastic-scattering cross sections were derived by least-square fitting the measured differential values with 6th-order Legendre-Polynomial series. The results of these fitting procedures were descriptive of the experimental results, as indicated in Fig. 2. The resulting angle-integrated elastic-scattering cross sections are shown in Fig. 1. Their estimated uncertainties were $\approx$ 5% and they are consistent to well within that estimate. These angle-integrated elastic-scattering cross sections are inclusive of inelastic-scattered components due to the excitation of the first-excited levels, as noted above. The present differential and angle-integrated elastic-scattering cross sections are in good agreement with lower-energy results previously reported from this laboratory,[11] as illustrated in Fig. 1. More generally, the prior data base should be reasonably summarized by ENDF/B-V[2] and comparisons of the present experimental elastic-scattering results with that evaluated data set are discussed below.

The broad resolutions employed in the measurements and the complexity of the elemental level structure precluded detailed inelastic-scattering results. However, five lumped-level inelastic excitations were observed. The corresponding excitation energies are given in Table I. These are averages of a number of observations with uncertainties defined as the RMS deviations from the averages. Table I correlates these observed excitations with reported levels in both isotopes.[12] In all cases, the observed inelastic-neutron group is a composite of several components and, in some cases, of many components. Due to this complexity the correlations are only qualitative.

The angle-integrated inelastic-excitation cross sections were derived from the measured differential values by Legendre-Polynomial fitting as described above for elastic scattering. The polynomials were of low order as the observed differential distributions were nearly isotropic. The angle-integrated inelastic-scattering cross-section results are summarized in Fig. 3. The observed excitations of the 491 keV level are uncertain as the magnitudes were much smaller than the cross sections due to the elastic scattering of the second neutron group from the source reaction. Corrections were made for the latter contaminent but at the expense of considerable increases in the experimental uncertainties. Cross sections for the excitation of 1050 and 1436 keV levels are better defined and, in each case,

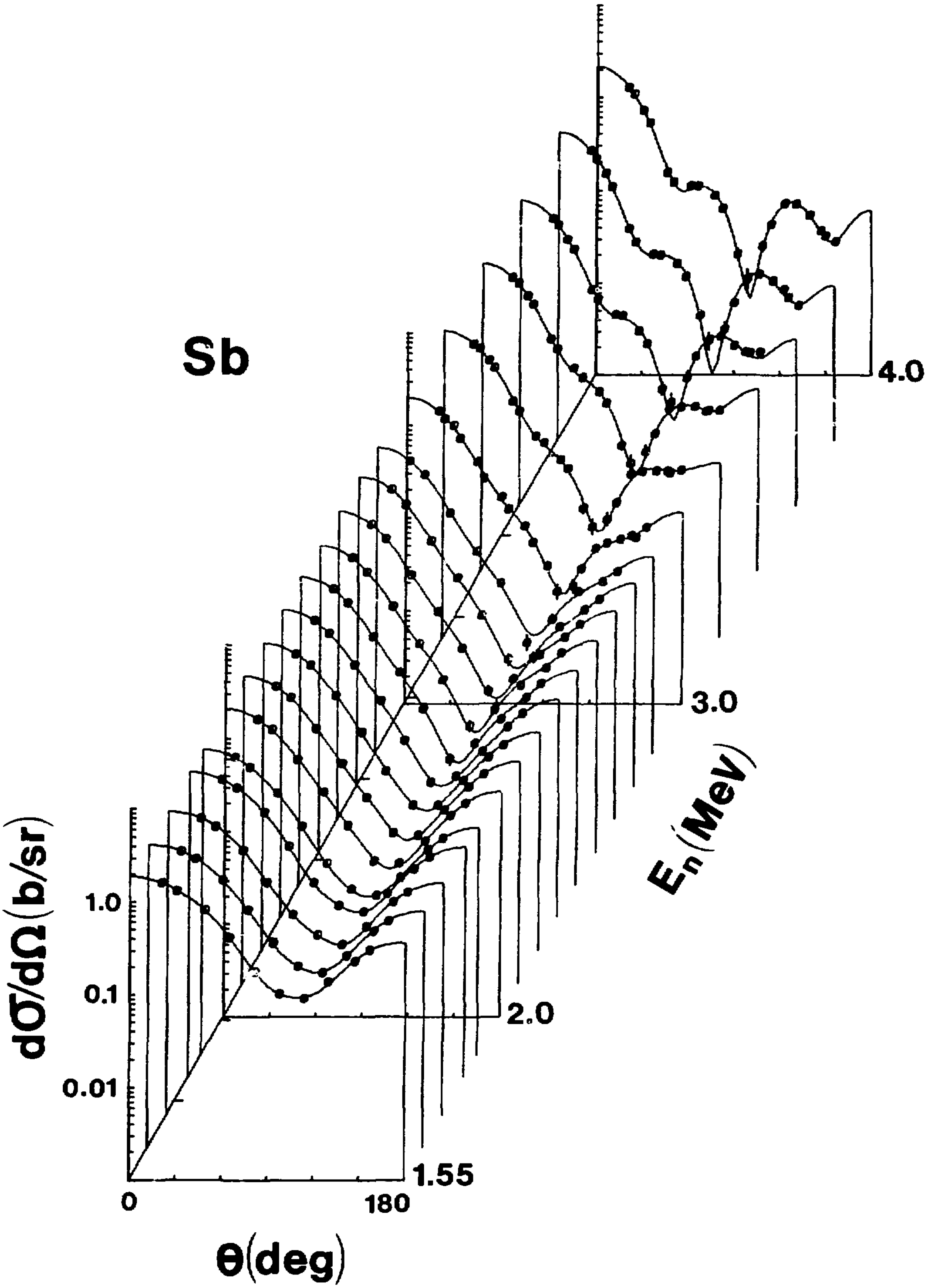

Fig. 2. Differential Elastic-Scattering Cross Sections of Elemental Antimony. The present experimental results are indicated by data symbols. Curves denote the results of fitting Legendre-Polynomial series to the measured quantities.

must consist of a number of components. The higher-energy excitations are less well known. The inelastic-scattering cross-section uncertainties, shown in Fig. 3, range from 15% to 30%. Their origins are similar to those described above for elastic scattering but with larger statistical components and with contributions due to corrections for the second-neutron component from the source reaction. The present inelastic-scattering results are consistent with the lower-energy values previously reported by this laboratory[11] and with the above neutron total and elastic-scattering cross-section results.

IV. MODEL DERIVATION AND DISCUSSION

It was assumed that the present experimental results could be described in terms of a spherical optical-statistical model(OM).[13] The model parameters were obtained by concurrently chi-square fitting the differential-elastic-scattering cross sections of Fig. 2, simultaneously varying the six parameters; real and imaginary strengths, radii and diffusenesses. A real-strength energy dependence of the form $V=V_o - 0.3\ E(\text{MeV})$ and a spin-orbit strength of 6 MeV were assumed. Compound-nucleus (CN) contributions were calculated using the Hauser-Feshbach formula,[14] with the corrections of Moldauer.[15] The excitation of discrete levels to energies of $\approx$ 1.1 MeV was explicitly calculated using the energies, spins and parities of ref. 12. Higher-energy excitations were described using the statistical formulation and parameters of Gilbert and Cameron.[16]

The application of the above procedures to the particular case of elemental antimony presents two additional problems. The two isotopes have different ground-state spins (5/2+ for ^{121}Sb and 7/2+ for ^{123}Sb). As noted above, the present measurements intentionally included neutrons due to the excitation of the first levels with those due to true elastic-scattering. The calculations were carried out using the program ABAREX[17] which has the capability to fit composite distributions such as those measured in this work. In this composite fitting the two isotopes behave similarly as they differ only in alternate ground and first-excited-level configurations; i.e. (7/2+ and 5/2+) and (5/2+ and 7/2+). The energies, and therefore the transmission coefficients, are similar. Because of the better known ^{123}Sb level structure, that isotope was assumed in most of the fitting procedures. The resulting parameters were then used as a starting point for fitting assuming a ^{121}Sb target. The ^{121}Sb-based parameters were essentially identical to those obtained with the ^{123}Sb target. The parameters were further verified by calculating the elemental CE contributions at each energy, subtracting them from the measured values to obtain the "experimental" shape-elastic (SE) cross sections and fitting the latter assuming only SE processes. After several iterations, the SE procedure led to parameters very similar to those obtained using the above ^{121}Sb and ^{123}Sb target assumptions. The two parameter sets obtained using the isotopic assumptions were averaged to obtain the elemental parameter set given in Table II. These parameters provide a reasonable description of the observed differential-elastic-scattering cross sections, as illustrated in Fig. 4, and of the neutron total and angle-integrated elastic-scattering cross sections, as illustrated in Fig. 1. However, there are some small discrepancies between measured and calculated results.

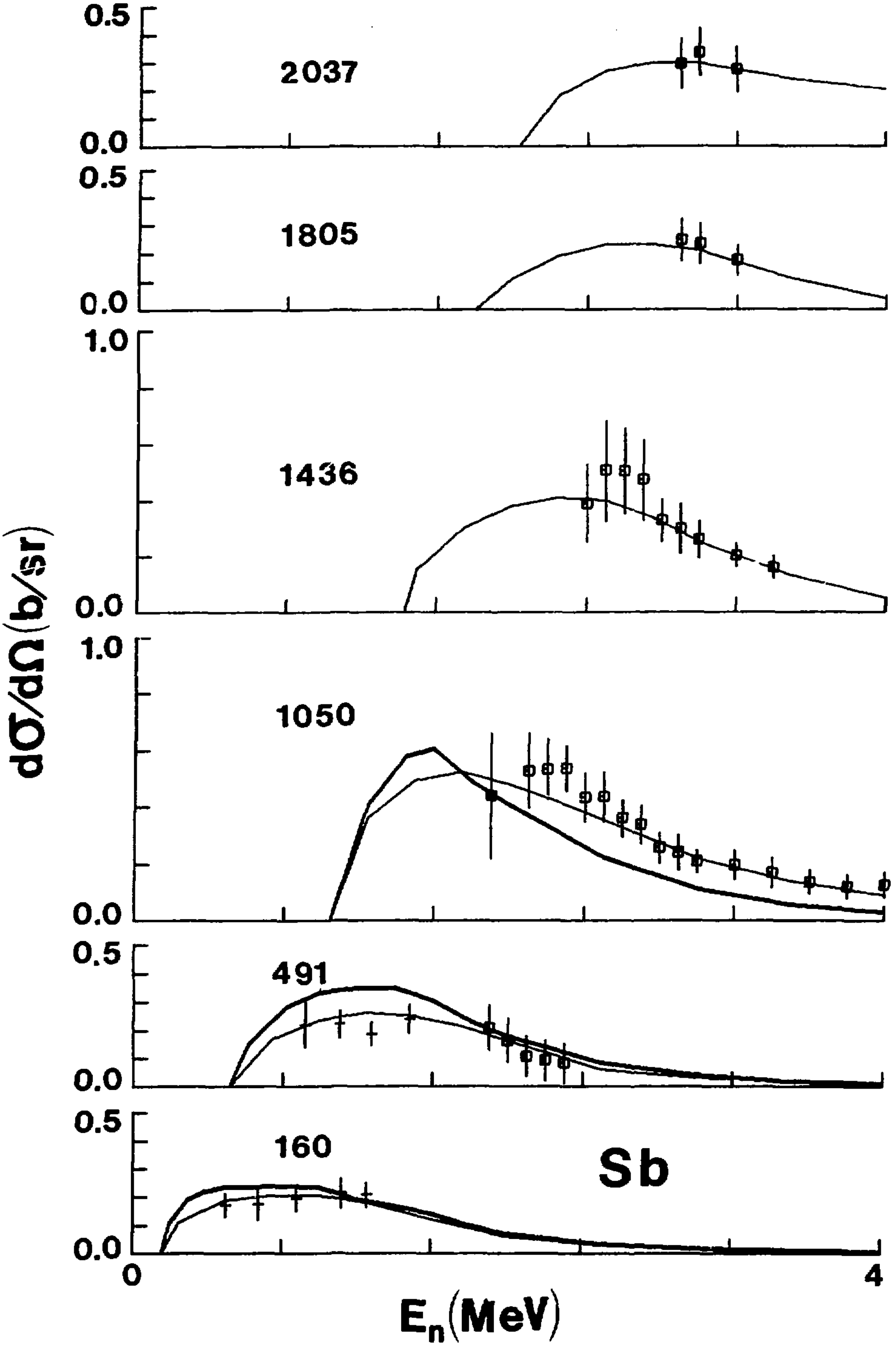

Fig. 3. Lumped-level Neutron-Inelastic-Excitation Cross Sections of Elemental Antimony. The present experimental results are indicated by □ , 200 keV averages of those of ref. 11 by +. Light curves are "eyeguides" and heavy curves indicate the results of calculations, as described in the text.

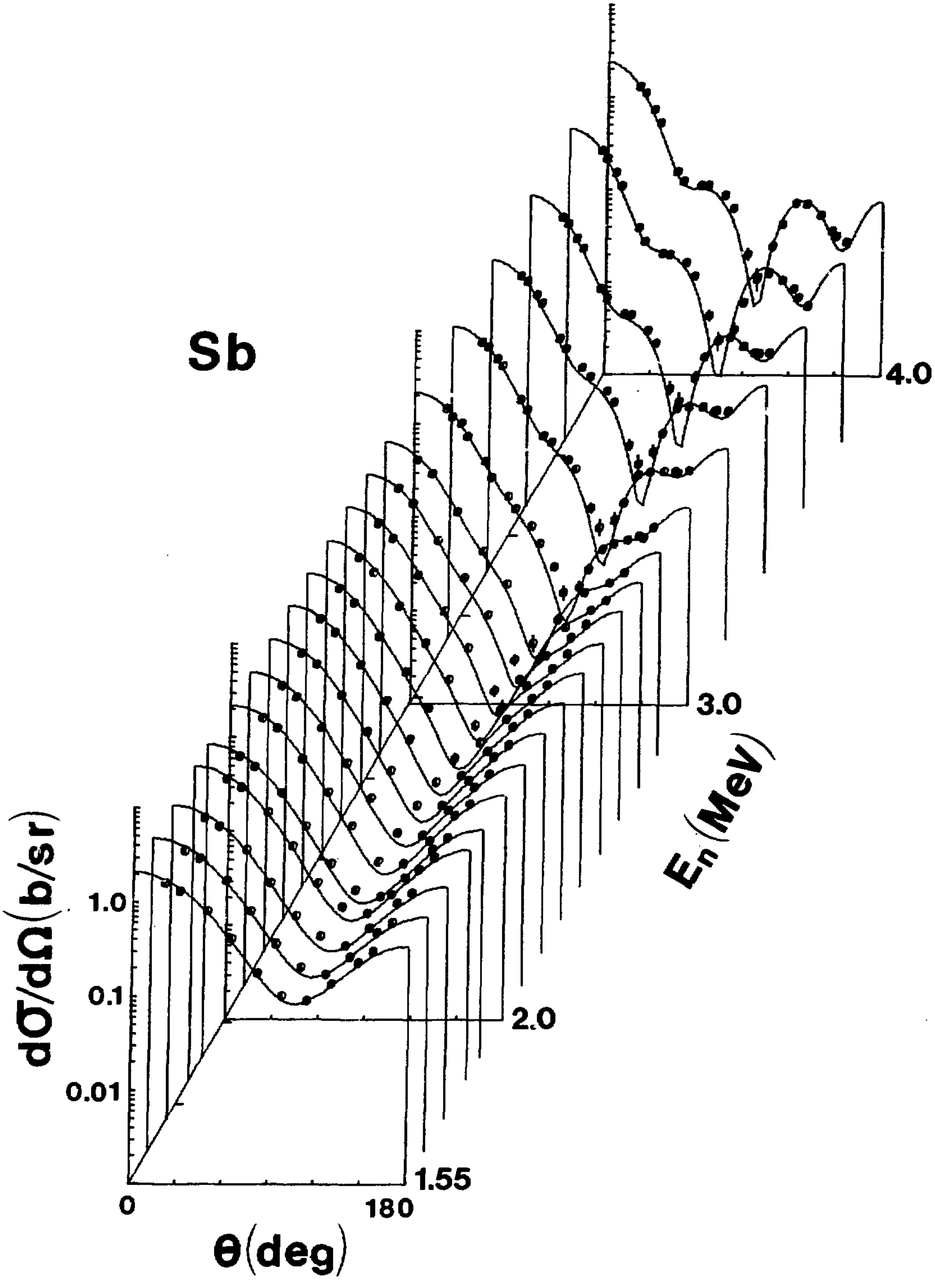

Fig. 4. Comparison of Measured and Calculated Differential-Elastic-Scattering Cross Sections of Elemental Antimony. The measured values are indicated by data symbols and the calculated results by curves.

In particular, the calculated differential-elastic-scattering cross sections, in the energy range $\approx$ 2.0 to 3.0 MeV, and near the minima of the distributions, are systematically smaller than the measured values. This suggests that the statistical representation of ref. [16] leads to excessive channel competition. This suggestion was not pursued by means of pragmatic statistical-parameter adjustments. Fig. 3 compares some measured and calculated angle-integrated inelastic-scattering cross sections. These comparisons are only qualitative as the correlation of lumped-level cross sections with discrete levels is somewhat uncertain. Despite this shortcoming, the agreement is good, excepting the excitation of the 1050 keV level. In the latter case the calculated quantities are systematically smaller than the measured values by amounts that cannot be reasonably attributed to level uncertainties. The discrepancy could again be symptomatic of excessive channel competition due to inappropriate statistical-level parameters. Generally, the OM parameters of Table 2 are consistent with those of a "regional" model applicable in this mass-energy region.[1]

V. COMPARISONS WITH ENDF/B-V

The ENDF/B-V evaluated-data-file system[2] contains ^{121}Sb and ^{123}Sb data sets. These isotopic components were combined to obtain elemental-evaluated-neutron total and elastic-scattering cross sections. The elastic-scattering file was constructed so as to include the first inelastic-scattered component (E_x=37 keV (^{121}Sb) and = 160 keV (^{123}Sb)) in order to make the evaluated results comparable with the present measured values. The measured and evaluated neutron total and elastic-scattering cross sections are compared in Fig. 5 and some relative numerical comparisons are given in Table III. At high energies the two neutron total cross sections are in good agreement. However, as the energy decreases below 3.0 MeV the measured values become increasingly larger than the evaluated quantities with differences amounting to 6%-8% at 0.5 MeV. Above 1.5 MeV the measured elastic-scattering cross sections are smaller than the evaluated quantities by more than 10% over a rather wide energy range. This difference is approximately twice the experimental uncertainty. The measured neutron total and elastic-scattering cross sections imply nonelastic cross sections that are essentially the total inelastic-scattering cross sections over the energy range of the present measurements (except for the excitation of the two low-lying levels, noted above). The nonelastic cross sections implied by the present measurements are larger than given by the evaluation by amounts that are generally several times the experimental uncertainties. This discrepancy is most serious between 1.5 and 3.0 MeV. The total inelastic-scattering cross sections are large in this region (e.g. 2 b and more).

VI. SUMMARY COMMENTS

The measurements improve the knowledge of energy-averaged neutron total cross sections of elemental antimony from $\approx$ 1.0 to 4.5 MeV. They also

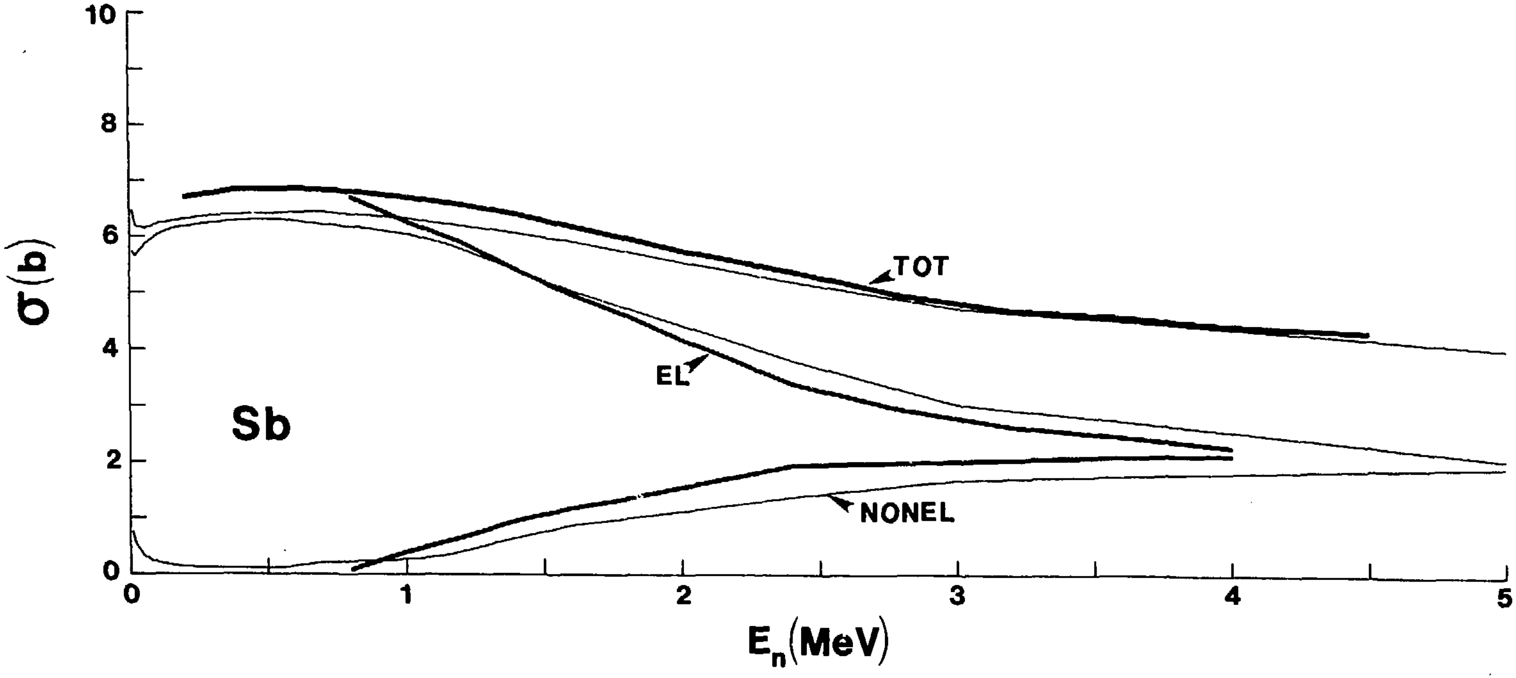

Fig. 5. Comparison of Measured and Evaluated Neutron Total and Elastic-Scattering Cross Sections of Elemental Antimony. "Eyeguides" constructed through the present measured values are indicated by heavy curves. Light curves indicate the respective quantities given by ENDF/B-V.[2] The evaluated elastic-scattering and nonelastic values include the excitation of the first two inelastic-neutron groups with the elastic-scattered component as defined in the text.

provide a good understanding of the effective energy-averaged differential-elastic-scattering cross sections from ≈ 1.5 to 4.0 MeV and of the corresponding angle-integrated elastic-scattering cross sections. In addition, the measurements give quantitative information about the broad-resolution inelastic-scattering cross sections. The parameters of a conventional spherical optical-statistical model were deduced from the observed differential-elastic-scattering cross sections. These parameters and the model reasonably described the observables. However, detailed comparisons of measured and calculated cross sections tend to suggest that the conventionally accepted statistical-level parameters are not entirely appropriate.[16] The model parameters are a consideration in the selection of a "regional" model applicable to the light fission-product region, described elsewhere.[1] The experimental results suggest that the ENDF/B-V neutron total cross sections are too small at lower energies and that the evaluated elastic-scattering cross sections are considerably too large in the mid-energy range (e.g. 1.5 to 3.0 MeV). Further, these discrepancies suggest that the evaluated total inelastic-scattering cross sections are too small by significant amounts.

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TABLE I. Observed Inelastic-Neutron Excitations in keV

No.	E_x(exp)	Reported Levels[a]	
		^{121}Sb	^{123}Sb
1	491±(?)	508(3/2+) 573(1/2+)	542(3/2+)
2	1050±32[b]	947(9/2+) 1024(7/2+) 1035(9/2+) 1139(11/2+) 1144(9/2+)	1030(9/2+) 1089(11/2+) 1183(+)
3	1436±33[b]	1386 1408 1410 1427 1446 1514 1521 1630 1660	1262 1324 1338 1511 1577 1601 1643 1653
4	1805±30[b]	1740 1820	1730 1740 1810 1860
5	2037±30[b]	1980 +many	2026 +many

[a] As given in Ref. 12; some additional J-pi values are given therein.

[b] RMS deviation from the average of a number of measurements.

TABLE II. Optical-Model Parameters for Elemental Antimony

Real Potential[a]

Strength V_o = 48.36 MeV

Radius[b], r_v = 1.245 F

Diffuseness, a_v = 0.620 F

J_v/A [d] = 429.8 MeV · F^3

Imaginary Potential[c]

Strength, W = 5.60 MeV

Radius[b], r_w = 1.210 F

Diffuseness, a_w = 0.627 F

J_w/A [d] = 53.9 MeV · F^3

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[a] Assume saxon form, energy dependence $V = V_o - 0.3 \cdot E(\text{MeV})$, and spin-orbit term of Thomas form with 6 MeV strength.

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

[c] Saxon-derivative form.

[d] Strength expressed as integral per nucleon.

TABLE III. Comparisons of Measured and Evaluated Cross Sections

E_n(MeV)	$\frac{\text{ENDF-EXP}}{\text{ENDF}}$ (in percent)		
	σ_t	σ_{el}	σ_{nonel}
1.0	-6.0	-	-
1.5	-3.5	0	-51
2.0	-3.9	+6	-40
2.5	-2.0	+11	-30
3.0	0.0	+10	-16
3.5	0.0	+11	-13
4.0	-1.6	+11	-11
4.5	-2.5	-	-