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Fast-Neutron Elastic-Scattering Cross Sections of Elemental Tin*

by

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ABSTRACT

Broad-resolution neutron-elastic-scattering cross sections of elemental tin are measured from 1.5 to 4.0 MeV. Incident-energy intervals are ≈ 50 keV below 3.0 MeV and ≈ 200 keV at higher energies. Ten to twenty scattering angles are used, distributed between ≈ 20 and 160°. The experimental results are used to deduce the parameters of a spherical optical-statistical model and they are also compared with corresponding values given in ENDF/B-V.

I. INTRODUCTION

The present work was undertaken as part of a comprehensive study of fast-neutron interactions with the light-mass fission products including neutron total, scattering and capture cross sections[1-7]. The tin isotopes are at the upper extreme of the light-mass fission-product yield distribution. Typically, their fission-product yields are ^{112}Sn (0.1%), ^{114}Sn(0.05%), ^{115}Sn(0.03%), ^{116}Sn(0.044%), ^{117}Sn(0.042%), ^{118}Sn(0.041%), ^{119}Sn(0.041%), ^{120}Sn(0.42%), ^{122}Sn(0.045%) and ^{124}Sn(0.056%) for ^{239}Pu fission induced by thermal neutrons. These are relatively small values. However, the neutron interaction with tin is of fission-product significance as it is a basis for model parameters that are generally applicable in this mass region. The present work was undertaken in order to provide an experimental foundation and to derive therefrom a representative set of model parameters. The latter were subsequently employed in the formulation of a "regional" model applicable to the light-mass fission products[8]. Elemental tin consists of the ten isotopes ^{112}Sn(1.0%), ^{114}Sn(0.86%), ^{115}Sn(0.35%), ^{116}Sn(14.4%), ^{117}Sn(7.6%), ^{118}Sn(24.1%), ^{119}Sn(8.6%), ^{120}Sn(32.8%), ^{122}Sn(4.7%) and ^{124}Sn(5.8%). These isotopes cover a large range of the nuclear asymmetry parameter, $(N-Z)/A$. However, the isotopic abundance is concentrated in the three isotopes ^{116}Sn, ^{118}Sn and ^{120}Sn. Thus the present elemental measurements and model are representative of the neutron interaction with targets having similar asymmetries.

Subsequent portions of this paper address; i) a brief outline of the experimental method, ii) the experimental results, iii) the derivation of an optical-statistical model (OM) from the measured values, and iv) comparisons of the experimental results with the evaluated quantities given in ENDF/B-V[9].

II. BRIEF OUTLINE OF THE EXPERIMENTAL METHOD

The measurements were made using the time-of-flight technique with the Argonne ten-angle detection apparatus[10]. 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 a cylinder of elemental tin 2 cm in diameter and 2 cm long placed 13 cm from the neutron source at a zero-degree source-reaction angle. Ten proton-recoil-scintillation detectors were placed $\approx$ 5.4 m from the scattering sample distributed over scattering angles from 20 to 160°. The relative scattering angles were known to ± 0.2° and the absolute angular scale to ± 0.6°. The relative detector efficiencies were determined by the observation of neutrons emitted from the spontaneous fission of ^{252}Cf[11]. The absolute normalization of the detector efficiencies was determined relative to the neutron total cross sections of elemental carbon[12] in the manner described in ref. 13. These procedures implied that the differential-scattering measurements were made relative to the neutron total cross sections of carbon. The experimental results were corrected for multiple-event, beam-attenuation and angular-resolution effects using a combination of Monte-Carlo and analytical procedures as described in ref. 14. Generally, details of the measurement method are set forth in ref. 14.

III. EXPERIMENTAL RESULTS

The measurements were made from 1.5 to 4.0 MeV with incident-energy spreads of 40 to 70 keV. Below 3.0 MeV the incident-energy-measurement interval was ≈ 50 keV and ten scattering angles were used. In order to reduce the effect of any possible cross-section fluctuations the results obtained at adjacent incident energies were averaged to a single distribution. At energies above 3.0 MeV the measurements were made at 200 keV incident-energy intervals and twenty scattering angles. The statistical uncertainties of the individual differential elastic-scattering measurements were $\lesssim$ 1% excepting the minima regions of the higher-energy distributions where they were larger. The uncertainties associated with the detector normalizations were ≈ 3% and those due to the correction procedures $\lesssim$ 1%. Thus, the overall uncertainties of the measured differential-elastic-scattering cross sections were $\lesssim$ 5%. The energy-averaged elastic-scattering results are summarized in Fig. 1. The corresponding numerical values have been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory. The angle-integrated elastic-scattering cross sections were derived from the measured differential values by least-squares fitting the observed differential distributions with 6th-order Legendre-Polynomial series. The results of these fitting procedures were descriptive of the observations, as illustrated in Fig. 1. The corresponding angle-integrated elastic-scattering cross sections are shown in Fig. 2. Their uncertainties are $\lesssim$5%. The energy-averaged experimental results displayed no evidence of energy-dependent fluctuations. There have been a number of previously reported measurements of differential-elastic scattering from elemental tin as referenced in CINDA[16]. These prior results should be reasonably summarized by the evaluations of ENDF/B-V[9] and comparisons with those evaluations are discussed below.

Neutrons due to inelastic-scattering processes were observed in the course of the above elastic-scattering measurements. They corresponded to relatively high excitation energies and were attributed to contributions from a number of isotopes. The primary purpose of the present measurements was the acquisition of precise energy-averaged elastic-scattering cross sections. To achieve that objective, relatively broad incident-energy spreads were used and these precluded detailed resolution of the complex inelastic-neutron components. Therefore, cross sections were not derived from the inelastic-neutron data. Detailed experimental studies of the inelastic-scattering process in tin will be reported later.

IV. MODEL DERIVATION

It was assumed that the present experimental results could be described in terms of a the spherical optical-statistical model (OM)[17]. Approximately

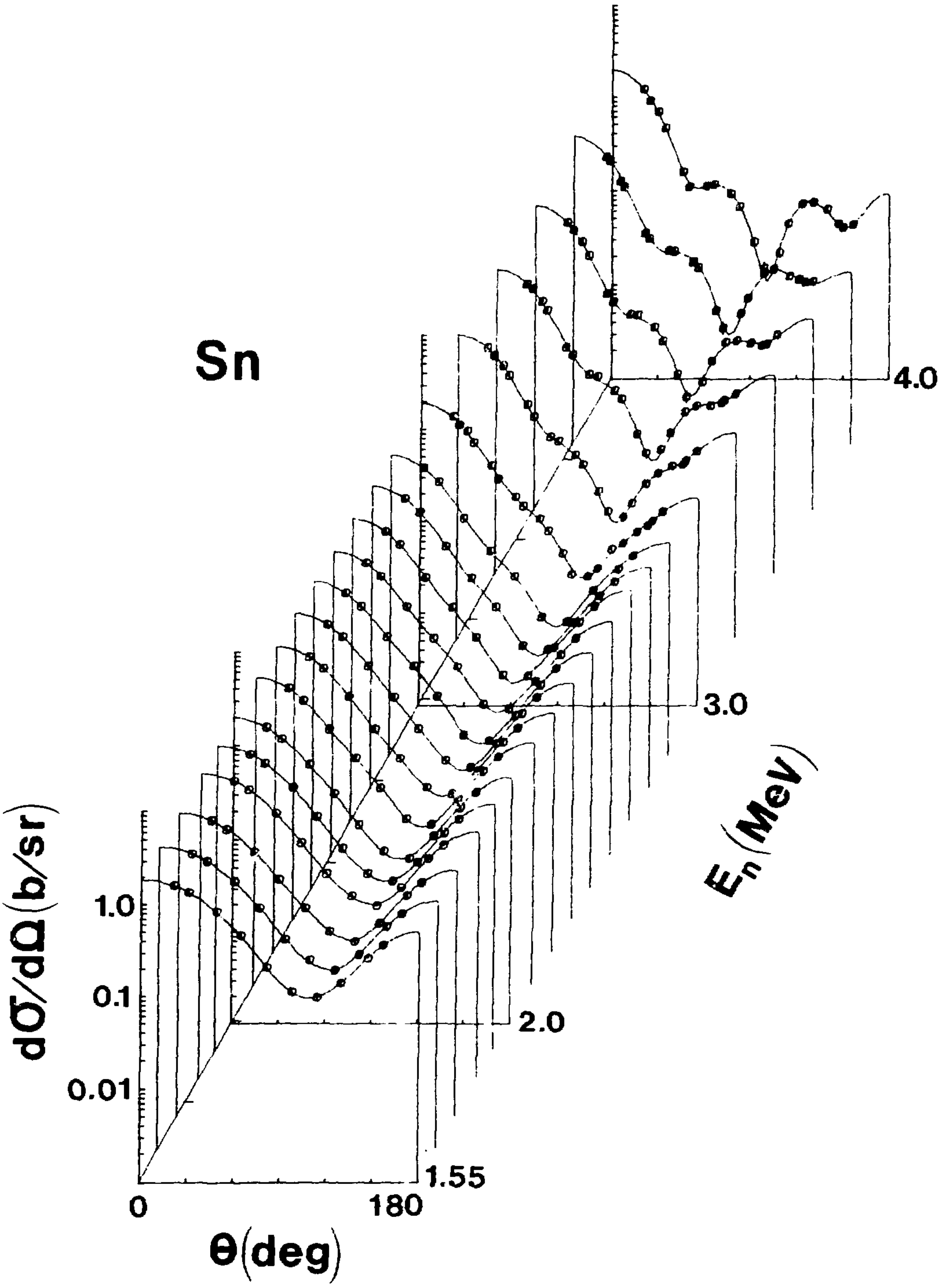

Fig. 1. Measured Differential-Elastic-Scattering Cross Sections of Elemental Tin. The present experimental results are indicated by data symbols and curves are the results of Legendre-Polynomial fits to the data.

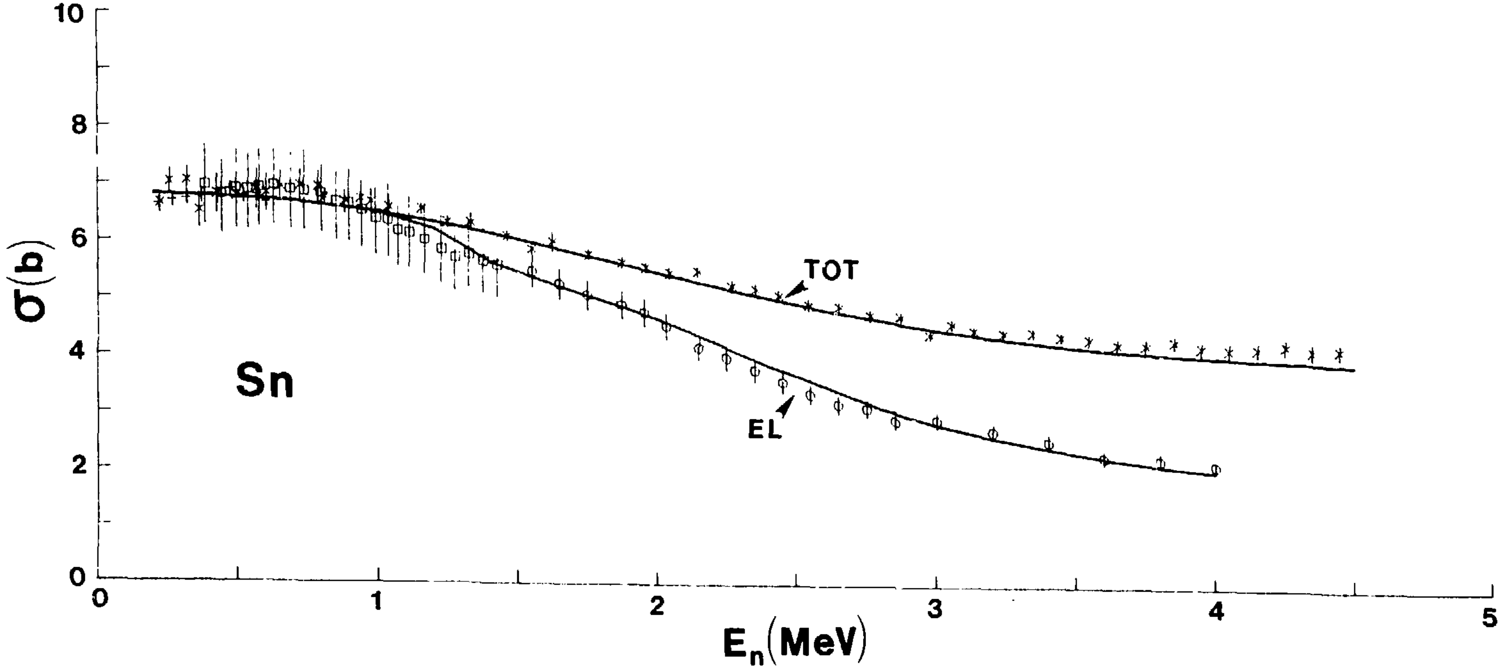

Fig. 2. Neutron Total and Angle-Integrated Elastic-Scattering Cross Sections of Elemental Tin. The present experimental results, and lower-energy (< 1.5 MeV) elastic-scattering results of ref. 15, are noted by O and a 50 keV average of the neutron total cross sections of ref. 1 by X. Curves indicate the results of calculations as described in the text.

85% of the element consists of even isotopes and that portion is primarily due to the three isotopes ^{116}Sn, ^{118}Sn and ^{120}Sn. Therefore, this OM derivation assumed an elemental mass of 118.8 AMU and the level structure of ^{118}Sn as reasonably representative of that of the element. In the energy range of the present measurements compound-nucleus processes are prominent. They were calculated using the Hauser-Feshbach formula[18], as modified by Moldauer[19]. The excitation energies and J-π values of ^{118}Sn were taken from ref. 20 up to excitations of 2.4 MeV. Higher-energy excitations were described in terms of the statistical formalism and parameters of Gilbert and Cameron[21]. All of the calculations were carried out using the computer code ABAREX[22].

The entire elastic-scattering data base (Fig. 1) was concurrently chi-square fitted, simultaneously varying the six parameters; real and imaginary strengths, radii and diffusenesses. The real strength was assumed to have an energy dependence of the form $V = V_o - 0.3 \cdot E$ (MeV). In addition, a 6 MeV spin-orbit potential of the Thomas form was assumed. The fitting procedure rapidly converged to the parameters of Table 1. The real parameters are similar to those reported in the literature[23]. The imaginary strength is relatively small, as previously reported near shell closures[24] ($Z = 50$ for tin). The parameters of Table 1 give a good description of the observed differential-elastic-scattering cross sections, as illustrated in Fig. 3. More than 95% of the measured values are consistent with the calculated quantities to within the experimental uncertainties. The parameters of Table 1 provide a good description of the angle-integrated elastic-scattering cross sections and of the neutron total cross sections of ref. 1 as illustrated in Fig. 2.

The agreement between observation and calculation supports the consideration of the OM parameters of Table 1 in the formulation of a "regional" OM applicable to the light-mass fission-product region.

V. COMPARISONS WITH ENDF/B-V

The ENDF/B-V[9] evaluated data file gives neutron cross sections of tin on an isotopic basis. These isotopic components were combined to obtain an evaluated elemental file for comparisons with the present experimental values. The results of such comparisons are summarized in Fig. 4 and Table 2. Above several MeV, the experimental neutron total cross sections of ref. 1 are consistent with those of the file. At lower energies the measured values are larger than the evaluated quantities by a few percent. This difference is reflected in comparisons of lower-energy measured and evaluated elastic-scattering cross sections as the radiative-capture cross sections are relatively small above several-100 keV. However, in the energy range of the present experiments the evaluated and measured elastic-scattering cross sections differ by large amounts: e.g. up to 20-30%. The latter discrepancies are far beyond the relevant experimental uncertainties or reasonable contributions from the low-lying levels of ^{119}Sn(8.6% abundant). In addition, the evaluated elastic-scatter-

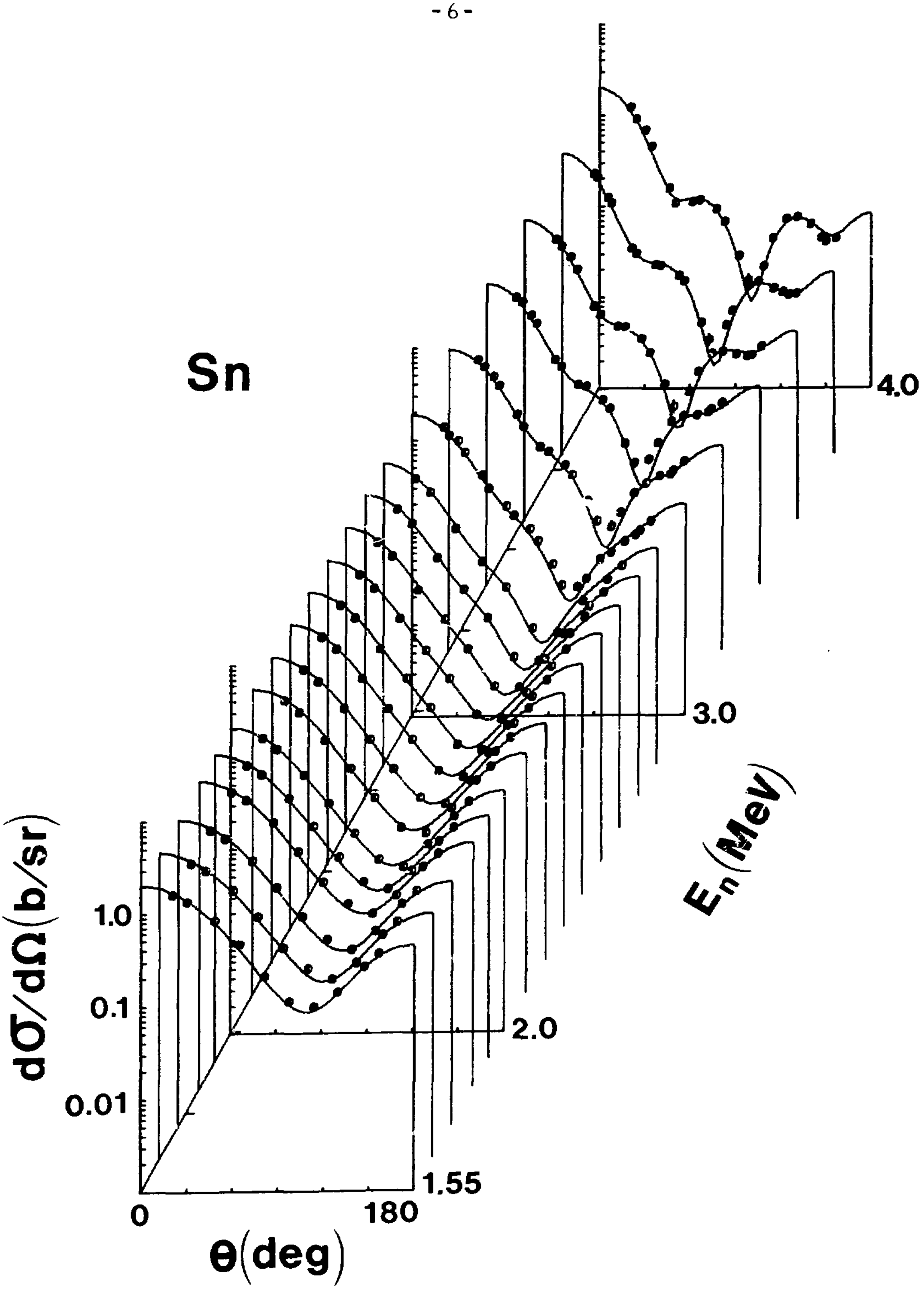

Fig. 3. Comparisons of Measured (symbols) and Calculated (curves) Neutron Differential-Elastic-Scattering Cross Sections of Elemental Tin.

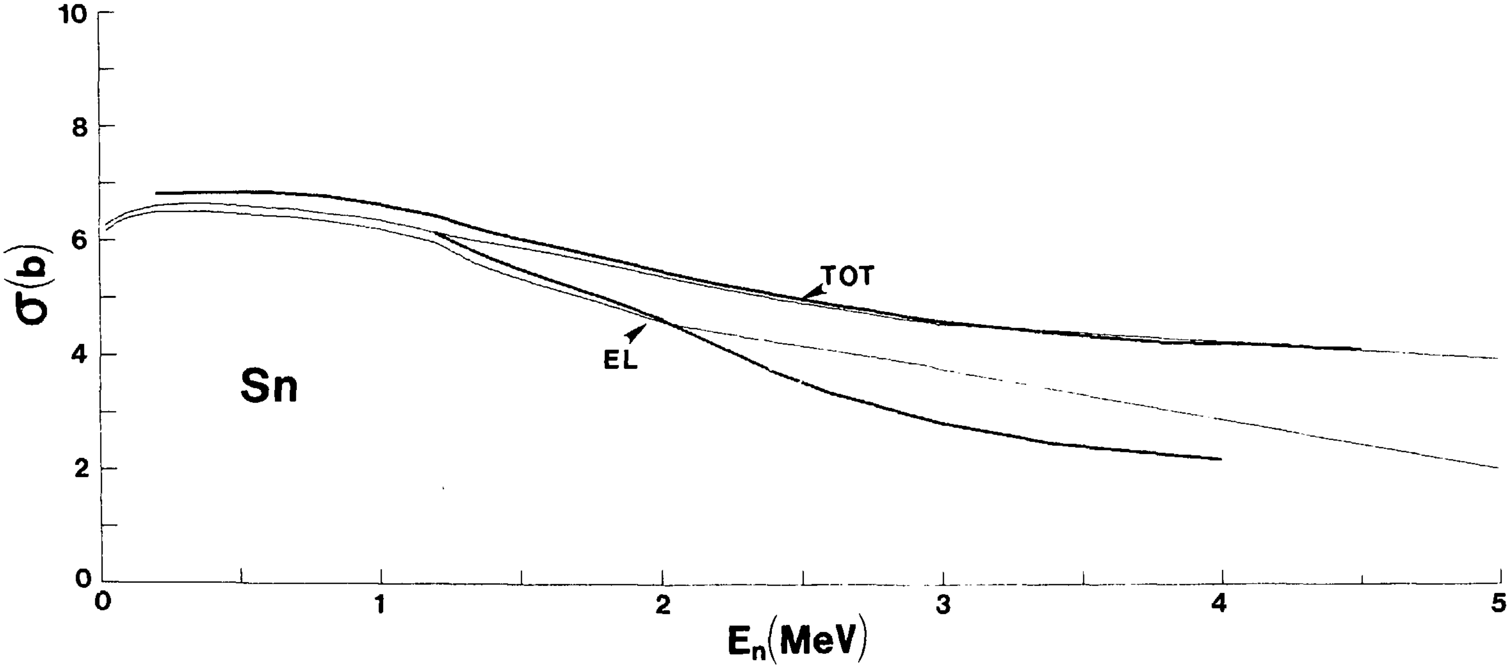

Fig. 4. Comparison of Measured and Evaluated Neutron Total and Elastic-Scattering Cross Sections of Elemental Tin. "Eyeguides", constructed through the present experimental results and those of ref. 1, are indicated by heavy curves. Light curves denote the comparable values implied by ENDF/B-V[9].

ing cross sections at higher energies, extending up to 20 MeV, appear to have shapes that are not consistent with a conventional OM. The above situation results in considerable differences between measured and evaluated nonelastic cross sections amounting to more than 100% at some energies. At the energies of the present measurements the nonelastic cross sections are essentially the total inelastic-scattering cross sections. Thus the nonelastic discrepancies are equivalent to inelastic-scattering discrepancies. They are factors of up to five larger than the often cited 20% accuracy goal for fission-product inelastic-scattering cross sections.

VI. SUMMARY COMMENTS

The present experimental results give improved definition to neutron elastic-scattering from elemental tin over the energy range 1.5 to 4.0 MeV. The measured values were used to determine the parameters of a spherical optical-statistical model. The resulting parameters provided a good description of the observed differential-elastic-scattering cross sections and of recently measured neutron total cross sections[1] over the few-MeV range. The model parameters suggest a relatively weak absorption similar to that previously cited in regions of shell closure ($Z = 50$)[24]. The measured elastic-scattering cross sections are much smaller than the comparable elemental values deduced from ENDF/B-V[9], by amounts that considerably exceed the experimental uncertainties. The present experimental results, and the neutron total cross sections of ref. 1, imply nonelastic cross sections that are much larger than those given by the evaluation. These differences are reflected in similar large discrepancies between experimentally-implied and evaluated total-inelastic-scattering cross sections by amounts very much exceeding the frequently cited applied accuracy goals for fission-product inelastic-scattering cross sections.

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Table 1. Optical-Model Parameters for Elemental Tin

Real Potential

Strength[a]	$V_0 = 48.528$	MeV
Radius[b]	$r_V = 1.251$	F
Diffuseness	$a_V = 0.596$	F
$Vr^2 = 75.94$	MeV-F^2	
J_V/A[d] $= 434.86$	MeV-F^3	

Imaginary Potential

Strength[c]	$W = 7.04$	MeV
Radius	$r_W = 1.244$	F
Diffuseness	$a_W = 0.4707$	F
$Wa = 3.31$	MeV-F	
$J_W/A = 53.49$	MeV-F^3	

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

[b] All radii expressed as $R = r_0 \times A^{1/3}$.

[c] Saxon derivative form.

[d] Integral per nucleon given by J/A.

Table 2. Comparisons with ENDF/B-V

	$\frac{\text{ENDF-Exp.}}{\text{ENDF}}$		
E_n(MeV)	σ_{total}	$\sigma_{elastic}$	$\sigma_{nonelastic}$
0.5	-3.5%	---	---
1.0	-3.9%	---	---
1.5	-2.2%	- 3.4%	+ 5.5%
2.0	-1.3%	0.0%	- 7.5%
2.5	-1.0%	+15.8%	- 92.1%
3.0	-0.8%	+25.3%	-129.5%
3.5	+0.7%	+27.6%	- 85.0%
4.0	+0.5%	+24.1%	- 50.4%
4.5	+0.0%	---	---