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FAST-NEUTRON TOTAL AND SCATTERING
CROSS SECTIONS OF $^{103}\text{Rh}^*$

by

A. B. Smith, P. T. Guenther and J. F. Whalen

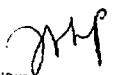
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TABLE OF CONTENTS

	<u>Page</u>
Abstract	1
I. Introduction	2
II. Experimental Methods	2
III. Experimental Results	2
IV. Interpretation	8
V. Comparisons with ENDF/B-V	10
VI. Summary Comment	10
Acknowledgements	12
References	13

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by

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Abstract

Fast-neutron total cross sections of ^{103}Rh are measured with 30 to 50 keV resolutions from 0.7 to 4.5 MeV. Differential elastic- and inelastic-scattering cross sections are measured from 1.45 to 3.85 MeV. Scattered-neutron groups corresponding to excited levels at 334 ± 13 , 536 ± 7 , 648 ± 25 , 796 ± 20 , 864 ± 22 , 1120 ± 22 , 1279 ± 50 , 1481 ± 27 , 1683 ± 39 , 1840 ± 79 , 1991 ± 71 and 2050 (tentative) keV are observed. An optical-statistical model is derived from the elastic-scattering results. The experimental values are compared with comparable quantities given in the ENDF/B-V evaluation.

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I. INTRODUCTION

This is the third report of a series dealing with the interaction of fast-neutrons with fission-product targets. Similar studies of palladium and silver are described in Refs. 1 and 2, respectively. The primary objectives of these studies were; 1) the determination of neutron cross sections in the low-MeV region for the derivation of an optical-statistical model (OM) suitable for the quantitative prediction of the interaction of fast neutrons with difficult-to-measure fission-product nuclei of similar mass, and 2) the provision of experimental information directly relevant to fission-product nuclei. Generalization of the individual OM parameter sets will be discussed in Ref. 3. The primary emphasis was on neutron total and elastic-scattering cross sections and, secondarily, on inelastic-scattering cross sections. Elemental rhodium is monoisotopic (^{103}Rh). It lies near the extreme peak of the light-mass fission-product-yield curve with, for example, a fission-product yield of $\approx 5.85\%$ for the fission of ^{239}Pu induced by fission-spectrum neutrons (i.e. by neutrons of energies similar to those encountered in a typical fast-breeding reactor).

Subsequent portions of this report deal with the experimental results, and their interpretation in terms of an OM, and with some comparisons with the corresponding values given in ENDF/B-V⁴.

II. EXPERIMENTAL METHODS

All of the measurements employed a 2 cm in diameter and 2 cm long cylinder of metallic rhodium. Chemical impurities within the sample were negligible. The sample density was determined to better than 1% by means of precision weight and dimension measurements. All neutron measurements were made using the $^7\text{Li}(p,n)^7\text{Be}$ reaction as a neutron source operating in the nsec-pulsed mode with associated time-of-flight techniques. The neutron total-cross-section measurements were carried out with the Argonne total-cross-section apparatus. The neutron differential-scattering measurements were made with the Argonne ten-angle time-of-flight system. The methods and apparatuses employed in both types of measurements were identical to those described in Refs. 1 and 2 and, indeed, the measurements were made concurrently with the palladium measurements of Ref. 1.

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

Neutron total cross sections were measured from ≈ 0.7 to 4.5 MeV at intervals of $\lesssim 50$ keV using monoenergetic-source techniques with resolutions in the range of 30 to 50 keV. The objective was the determination of energy-averaged total cross sections consistent with the concept of the OM. The measurements were made in several sets, each spanning the

experimental energy range. The results from the various sets were combined and averaged over 100 keV energy bins. The statistical uncertainties of the averaged values were $\lesssim 1\%$. Corrections were made for small dead-time effects. In-scattering and self-shielding corrections were negligible in the present experiments. The energy-averaged results are shown in Fig. 1. The present energy-averaged results decrease smoothly in magnitude with energy without any indication of energy-dependent fluctuations. The present values are in good agreement with recent results of white-source measurements by Poenitz et al.⁵ and the latter were used to extend the present measurements to lower energies as illustrated in Fig. 1. Concurrently with the rhodium measurements, neutron total cross sections of carbon were determined giving results in good agreement with those reported in the literature.⁶

B. Neutron Elastic-Scattering Cross Sections

Differential elastic-scattering cross sections were measured from ≈ 1.45 to 3.85 MeV. Below 3.0 MeV the measurements were made at ≈ 50 keV intervals and at ten scattering angles distributed between ≈ 20 and 160 degrees. At 3.0 MeV and above the measurements were made at ≈ 100 keV intervals and twenty scattering angles distributed over the same angular range. The objective was reliable energy-average cross sections, thus broad (≈ 30 to 70 keV) resolutions were employed in the measurements and, below 3.0 MeV, results obtained at adjacent energies were averaged. The broad experimental resolutions contributed to an energy-smooth cross-section behavior and good statistical accuracies but precluded the resolution of elastic-scattered neutrons from inelastic-scattered neutrons associated with the excitation of the first two levels at ≈ 39 and 93 keV. Thus it should be clearly understood that, the measured "elastic" cross sections referred to here are inclusive of two small inelastic-neutron components. The latter are dealt with in the interpretation described below. The differential neutron scattering measurements were made relative to the neutron total cross sections of carbon⁶ in the manner described in Ref. 8. Neutron scattering angles were determined to a relative uncertainty of ± 0.1 degree and an absolute uncertainty of ± 0.75 degree. The statistical uncertainties of the individual differential elastic-scattering cross sections was $\lesssim 1\%$ with larger uncertainties at the extreme minimum of the distributions. Systematic differential-cross-section uncertainties, largely associated with detector calibration, were $\approx 3\%$. The measured results were corrected for multiple-event, beam-attenuation and angular-resolution effects using the correction procedures of Ref. 9. Generally, these correction procedures introduced a 1% uncertainty into the cross-section values. Thus the overall differential-cross-section uncertainty was $\lesssim 5\%$.

The measured differential "elastic"-scattering results are summarized in Fig. 2. These differential values were least-square fitted with 6th-order Legendre-Polynomial series in order to obtain the angle-integrated elastic scattering cross sections shown in Fig. 1. The quality of the Legendre-polynomial description of the differential values is indicated by the curves of Fig. 2. The uncertainties of the angle-integrated cross sections are $\lesssim 5\%$. The present elastic-scattering results reasonably extrapolate to the lower-energy values of Ref. 7 as illustrated in Fig. 1.

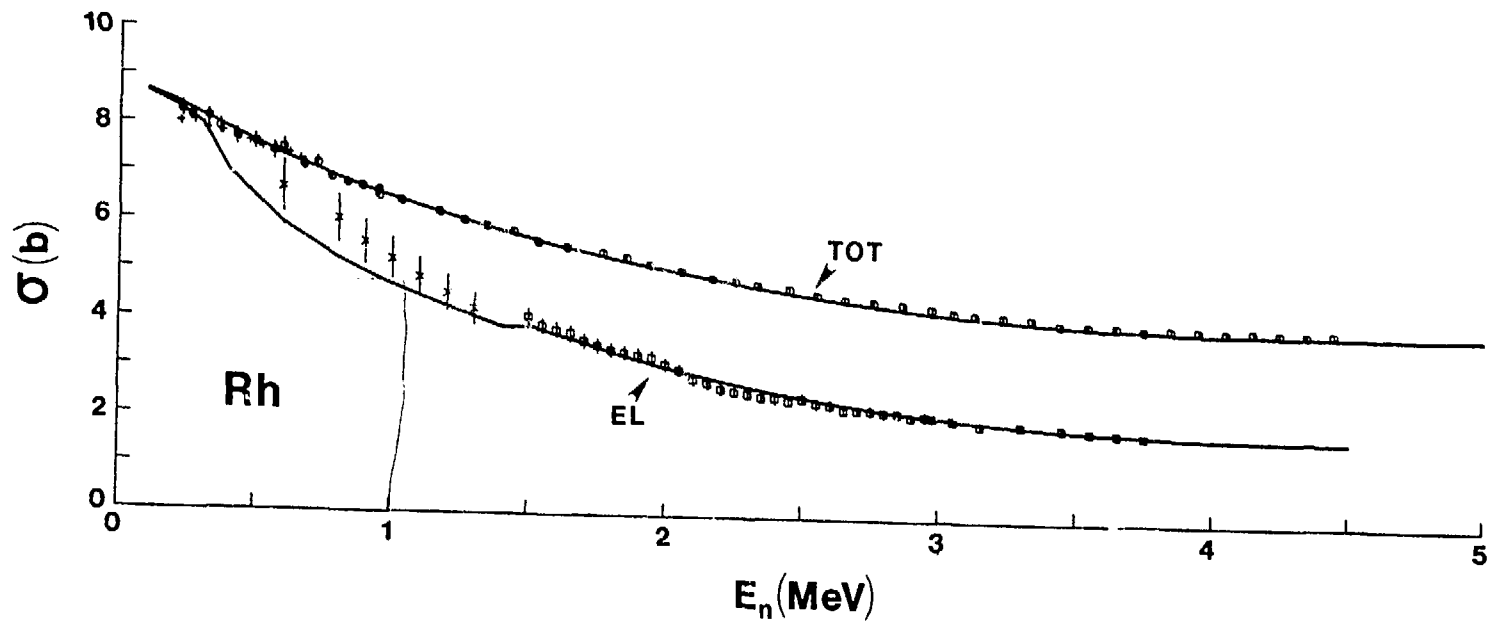


Fig. 1. Neutron Total and "Elastic"-Scattering Cross Sections of ^{103}Rh . The present experimental results are indicated by \circ (totals) and \square (elastic-scattering) symbols. Total-cross-section results are extended to energies below 700 keV using values of Ref. 5. Lower-energy elastic scattering results of Ref. 7 are indicated by X symbols. Curves indicate the results of OM calculations as described in the text.

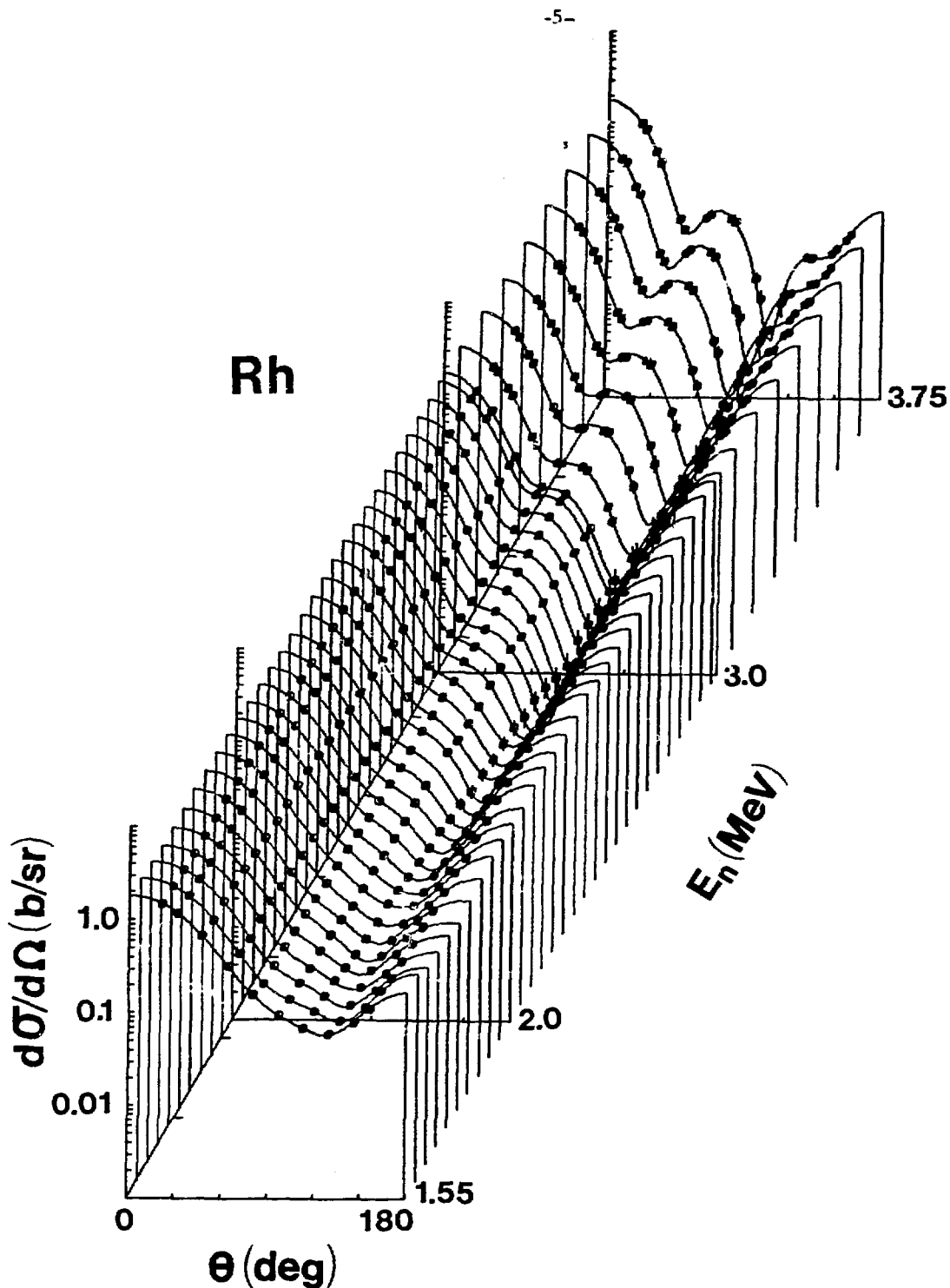


Fig. 2. Differential "Elastic"-Scattering Cross Sections of ^{103}Rh . The present experimental results are indicated by data symbols. Curves indicate results of fitting Legendre-Polynomial series to the measured values.

C. Neutron Inelastic-Scattering Cross Sections

The primary goal of the measurements was the determination of neutron total and elastic-scattering cross sections. However, inelastic-scattering cross sections were crude in the course of the "elastic"-scattering measurements. The intentionally-broad incident-energy spreads precluded the resolution of neutrons associated with the excitation of the low-lying 39 and 93 keV levels (as noted above), and restricted the resolution of inelastic-neutron groups corresponding to the excitations of higher-lying levels. Twelve inelastic-neutron groups were observed corresponding to the excitations of levels up to ≈ 2.0 MeV as summarized in Table 1. In only two of these cases could the observed excitations be reasonably attributed to a single level. The remainder appear to be composites of contributions from two or more levels. Further definition of these components will be pursued in future measurements to be reported elsewhere.¹⁰ The observed excitation energies of Table 1 are simple averages of results of a number of measurements with the uncertainties defined as the RMS deviations of the observables from the averages. Thus the uncertainties apply to the mean excitation energies and do not necessarily correspond to scattered-neutron resolutions. The latter were governed by the incident-neutron energy spreads and the scattered-neutron resolutions of the apparatus. Generally, the observed excitation energies are reasonably consistent with the detailed level structure determined by means of $(n; n', \gamma)$ measurements⁷ and radioactive decay studies¹¹ up to ≈ 1300 keV (see Table 1). Knowledge of higher-energy levels remains very fragmentary.

Inelastic-scattering cross-section determinations extended in incident energy from ≈ 800 keV above threshold to 3.85 MeV. The measured differential values were corrected for multiple-event and beam-attenuation effects. Angle-integrated inelastic-scattering cross sections were derived from the measured differential values in the same manner as described above in the context of elastic scattering. The inelastic-scattered neutron distributions approached isotropy, thus the Legendre-Polynomial Series fitted to the measured values were of low order (e.g., ≤ 2). The origins of the uncertainties in the resulting cross sections were analogous to those for elastic scattering (above) with generally much larger statistical components. An additional uncertainty factor was the second neutron group from the ${}^7\text{Li}(p;n){}^7\text{Be}$ source reaction. This contribution was particularly a concern for the excitation of the 334 keV level where, over much of the measured energy range, the elastically-scattered second-group component was not resolved from the inelastic-neutron first-group. The requisite corrections for the second-source-neutron group increased the inelastic-cross-section uncertainties for a number of the excitations. Generally, the total inelastic-scattering cross-section uncertainties were in the range 10 to more than 30%. The experimental inelastic-scattering cross sections results are summarized in Fig. 3. Cross sections for the excitation of 796 and 864 keV levels are given as a composite sum in order to enhance accuracies. The figure also contains "eyeguides" for each excitation indicating energy-dependent trends. The sum of these "eyeguides" is consistent with the measured neutron total and elastic-scattering results discussed above. Also, the present inelastic-scattering results are reasonably consistent with the better resolution and lower-energy results of Ref. 7.

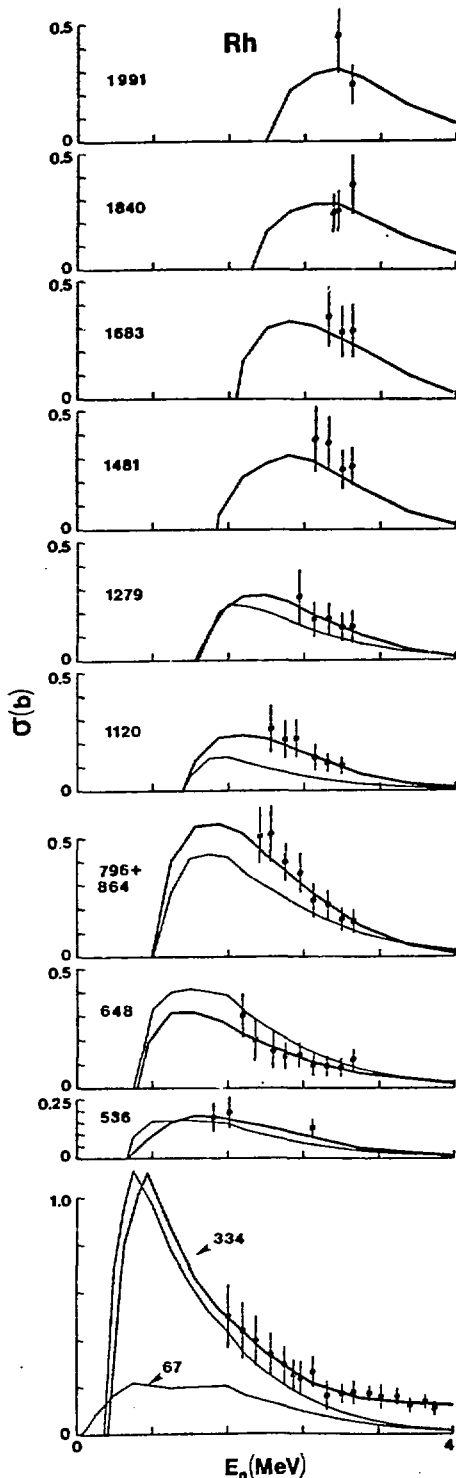


Fig. 3. Neutron Inelastic-Scattering Cross Sections of ^{103}Rh . Observed excitation energies are numerically given in the various sections of the figure. The present experimental results are indicated by circular data symbols. Heavy curves are "eyeguides" constructed through the measured values. Light curves indicate the results of model calculations as discussed in the text.

IV. INTERPRETATION

It was assumed that the fast-neutron interaction with ^{103}Rh could be described by a spherical optical-statistical model (OM)¹². The OM parameters were deduced from the observed differential elastic-scattering cross sections (see Fig. 1) by concurrently chi-square fitting the entire data base. The fitting procedure simultaneously varied the six OM parameters; real and imaginary strengths, radii and diffusenesses. The real strength was assumed to have an energy dependence of the form $V=V_0 - 0.3 \times E(\text{MeV})$, consistent with commonly used global potentials¹³. Compound-nucleus (CN) processes were calculated using the Hauser-Feshbach formula¹⁴ as modified by Moldauer¹⁵. The excitation of 17 discrete levels to energies of ≈ 1.4 MeV was considered using the energies and $J-\pi$ values of Ref. 7, supplemented by the compilation of Ref. 11. Higher-lying levels were statistically described using the parameters of Gilbert and Cameron¹⁶. All of the calculations were made with the computer code ABAREX¹⁷. This code is capable of fitting observed differential cross sections consisting of several components. That capability was utilized as the observed "elastic"-scattering cross sections included inelastic contributions associated with the excitation of 40 keV (7/2+) and 93 keV (9/2+) levels. These inelastic components made a small but significant contribution to the observed differential elastic-scattering cross sections results.

Following the above procedures, the OM parameters of Table 2 were obtained. The real and imaginary strengths (measured as integral per nucleon, J_v/A and J_w/A , or Vr^2 and $W \cdot a$, respectively) are similar to those generally applicable in this mass-energy region³. The imaginary radius is somewhat larger than the real radius as is found in potentials largely based on low-energy strength functions¹⁸. The parameters of Table 2 provide a good description of the observed differential "elastic"-scattering cross sections as illustrated in Fig. 4. They also nicely describe the observed neutron total and angle-integrated "elastic"-scattering cross sections as illustrated in Fig. 1. The small discontinuity in the elastic-scattering cross section near 1.5 MeV is due to the inclusion of the first two inelastic-scattering components to make the calculated and observed results consistent. The calculations indicate smaller low-energy elastic-scattering values than reported in Ref. 7.

Comparison of measured and calculated inelastic-scattering cross sections are complicated by the limited knowledge of excited levels and by the lack of experimental definition. However, measured and calculated results are compared to excitation energies of ≈ 1200 keV in Fig. 3. Cross sections calculated for the composite excitation ($\bar{E}_x = 67$ keV) of the 40 keV (7/2+) and 93 keV (9/2+) levels are indicated. There is no counterpart in the present measurements. The cross sections for the excitation of the 334 keV level (295 keV (3/2-) and 357 keV (5/2-)) are large. The calculated values are somewhat smaller than the measured results and increasingly so with energy. The measured values are not particularly well known due to corrections for contributions from the second-neutron group of the source reaction. However, the discrepancy is systematic and has the character and magnitude of a direct-vibrational process not consistent with a CN model. A similar behavior was noted in studies of the neutron interaction with silver as discussed in Ref. 2.

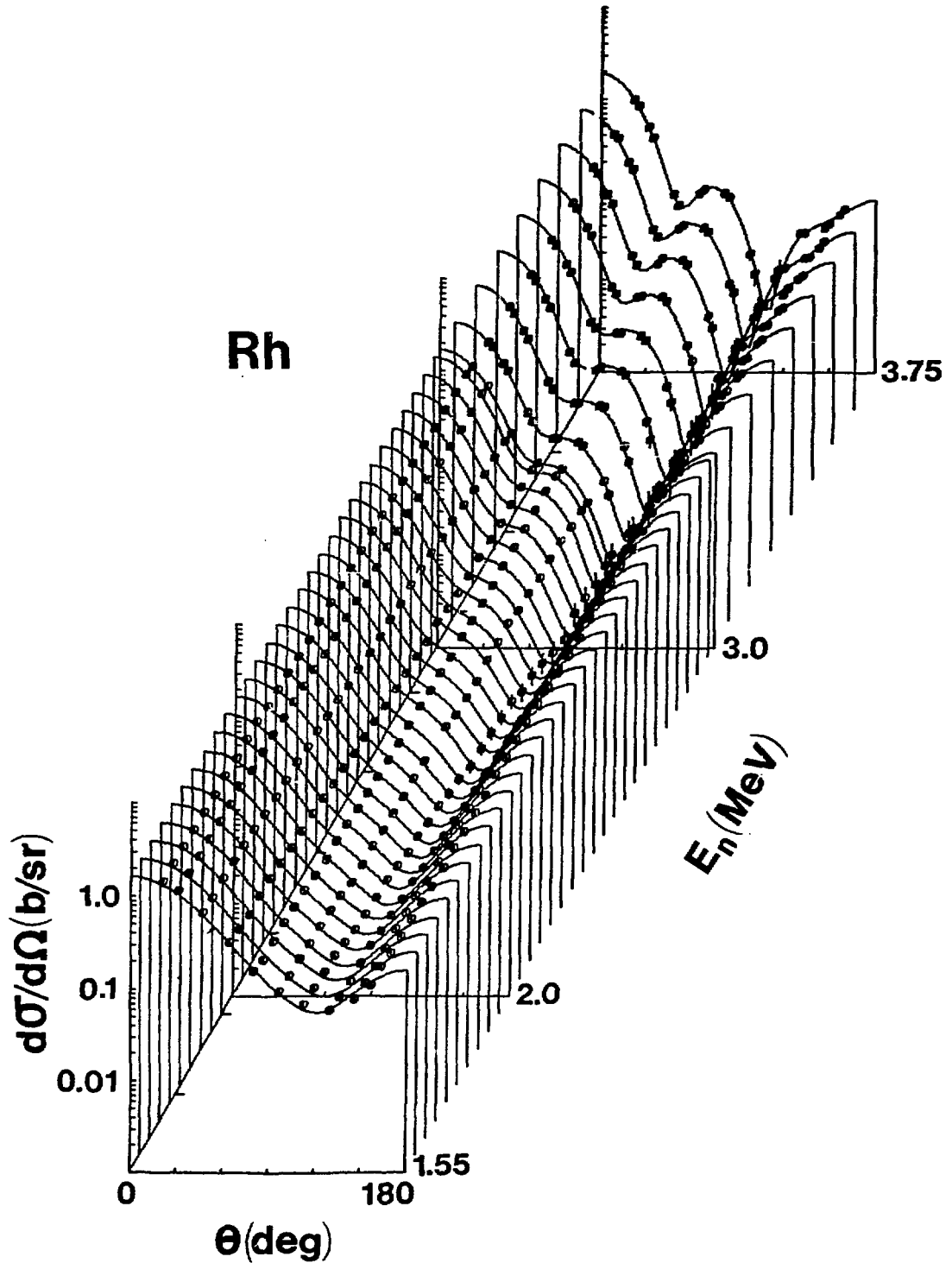


Fig. 4. Measured and Calculated Differential "Elastic"-Scattering Cross Sections of ^{103}Rh . Measured results are indicated by data symbols and calculated values by curves.

The cross sections for the excitation of the 536 keV(5/2+) level are small and there is reasonable agreement between measurement and calculation. The calculated cross sections for the excitation of the 648 keV(607(7/2+), 650 keV(5/2+) and 651 keV(3/2+)) level are marginally larger than the observed values. Calculated cross sections for higher-lying levels are universally smaller than the measured values. This discrepancy may be partly attributable to inappropriate J- π assignments and/or the omission of contributing levels in the calculations. The measured values are not definitive enough to effectively test either of these premises. Inappropriate statistical-level parameters may also be a concern but the usual symptom of incorrect channel competition are not in evidence.

V. COMPARISONS WITH ENDF/B-V

The prominent measured cross sections were compared with the corresponding values given in ENDF/B-V(MAT-1310)⁴. The evaluated neutron total cross sections are generally larger than the measured quantities as illustrated in Fig. 5 and Table 3. The differences range from small amounts (e.g., $\approx 1\%$) to as much as 8%. It is not clear to what extent a model played a part in the evaluation. If it was a significant consideration its parameters were not capable of reasonably describing the measured total cross sections over the 1 to 3 MeV region and the neutron total cross sections is the most readily calculated observable. The evaluated elastic-scattering cross sections are also generally bigger than the measured values by even larger amounts ($\approx 15\%$ at ≈ 2.5 MeV), as illustrated in Fig. 5 and Table 3. The nonelastic cross sections implied by the measurements are in good agreement with the evaluated total inelastic-scattering cross sections as illustrated in Fig. 5. This agreement maybe somewhat fortuitous in view of the discrepancies between measured and evaluated neutron total and elastic-scattering cross sections.

VI. SUMMARY COMMENT

The present measurements provide new definition of the ¹⁰³Rh neutron total cross sections in a region where previous knowledge was sparse or non-existent. The differential neutron "elastic"-scattering measurements provide a good knowledge of the "elastic"-scattering process in the low-MeV region. The observations provide some understanding of the neutron inelastic-scattering process but lack the resolution necessary to define the detailed excited-level structure. The elastic-scattering data was used to deduce a spherical OM potential, the parameters of which are consistent with those found generally applicable in this mass-energy region³. This potential provides a vehicle for the calculation of other neutron-induced processes (e.g., radiative capture) and/or for the extrapolation to nearby experimentally inaccessible fission products. The experimental results suggest that the evaluated neutron total and elastic-scattering cross sections as given in ENDF/B-V⁴ are too large by significant amounts throughout the few-MeV region.

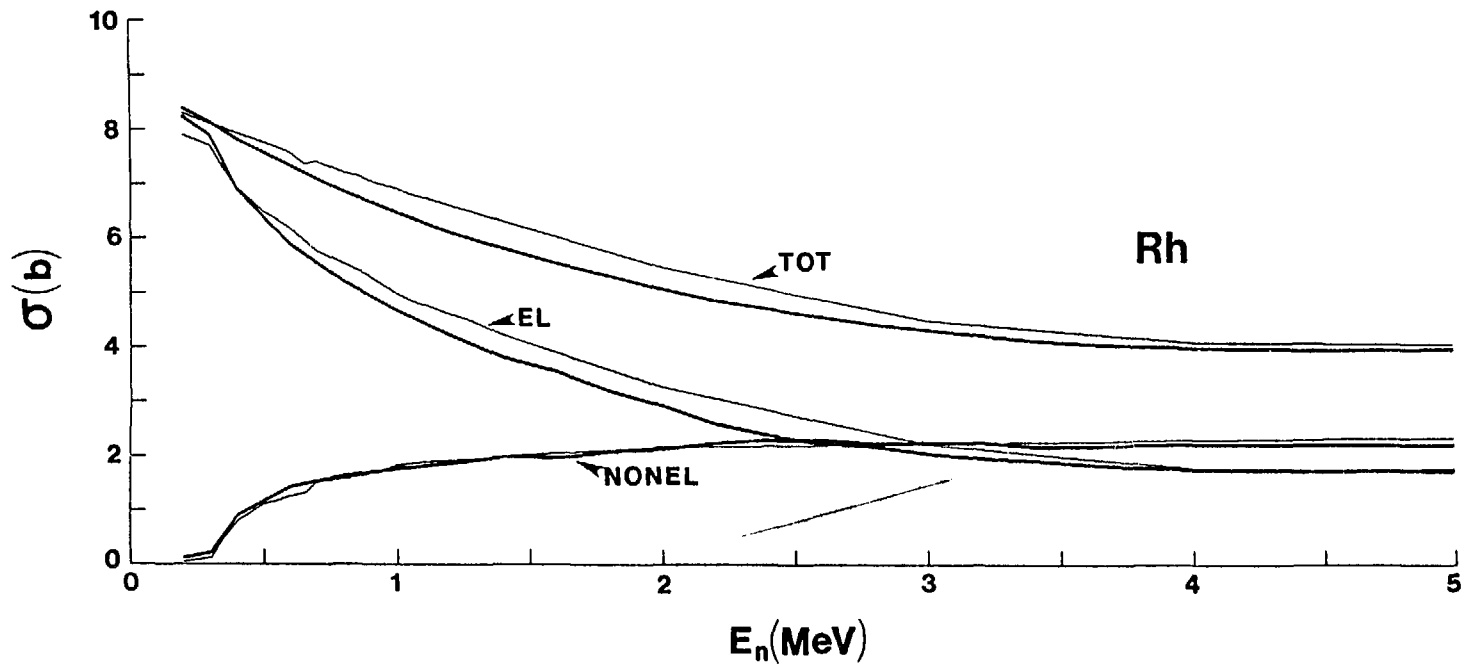


Fig. 5. Comparison of Measured and Evaluated Neutron Total, Elastic-Scattering and Nonelastic Cross Sections of ^{103}Rh . The heavy curves are "eyeguides" constructed through the present measured and calculated results. The light curves indicate the comparable quantities taken from ENDF/B-V4.

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TABLE 1. Observed Excitation Energies (in keV)

No.	E_x , Exp.	Reference 7
1	334 ± 13^a	295(3/2-), 357(5/2-)
2	536 ± 7	536(5/2+)
3	648 ± 25	607(7/2+), 650(5/2+), 651(3/2+)
4	796 ± 20	805(1/2-)
5	864 ± 22	847(7/20), 881(5/2-), 920(9/2-)
6	1120 ± 22	1106(5/2-)
7	1279 ± 50	1251(5/2+), 1277(3/2-), 1293(9/2-)
8	1481 ± 27	
9	1683 ± 39	
10	1840 ± 79	
11	1991 ± 71	
12	(2050)	

^aThe uncertainties are defined as the RMS deviation from the average of a number of measurements.

Table 2. Optical-Potential Parameters for Rhodium^a

Real Potential^b

$$V_0 = 46.896 \text{ MeV}$$

$$r_V^c = 1.266 \text{ F}$$

$$a_V = 0.686 \text{ F}$$

$$Vr^2 = 75.19 \text{ MeV-F}^2$$

$$J_V/A = 451.42 \text{ MeV-F}^3$$

Imaginary Potential^d

$$W = 10.988 \text{ MeV}$$

$$r_W^c = 1.319 \text{ F}$$

$$a_W = 0.431 \text{ F}$$

$$Wa = 4.74 \text{ MeV-F}$$

$$J_W/A = 89.75 \text{ MeV-F}^3$$

^aAlso a spin orbit term of the Thomas form with a 6 MeV strength.

^bSaxon form with energy dependence of $V = V_0 - 0.3 \cdot E(\text{MeV})$.

^cAll radii expressed as $R = r \cdot A^{1/3}$.

^dSaxon-derivative form.

Table 3. Comparisons with ENDF/B-V

E_n (MeV)	$\frac{\text{ENDF-EXP}}{\text{ENDF}}$	
	Totals	Elastics
.5	+2.3%	+1.5%
1.0	+6.0%	+6.0%
1.5	+8.0%	+8.6%
2.0	+7.3%	+10.0%
2.5	+6.6%	+15.4%
3.0	+3.8%	+8.6%
3.5	+4.6%	+5.0%
4.0	+2.0%	+2.0%
5.0	+2.0%	-2.0%