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FAST-NEUTRON TOTAL AND SCATTERING CROSS SECTIONS OF NIOBIUM*

by

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

July 1982

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Applied Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439
USA

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A. B. Smith, P. T. Guenther and
J. F. Whalen
Applied Physics Division
Argonne National Laboratory

ABSTRACT

Neutron total cross sections of niobium were measured from $\approx$ 0.7 to 4.5 MeV at intervals of $\lesssim$ 50 keV with broad resolution. Differerential-elastic-scattering cross sections were measured from $\approx$ 1.5 to 4.0 MeV at intervals of 0.1 to 0.2 MeV and at 10 to 20 scattering angles distributed between $\approx$ 20 and 160 degrees. Inelastically-scattered neutrons, corresponding to the excitation of levels at; 788 ± 23, 982 ± 17, 1088 ± 27, 1335 ± 35, 1504 ± 30, 1697 ± 19, 1971 ± 22, 2176 ± 28, 2456 ± (?), and 2581 ± (?) keV, were observed. An optical-statistical model, giving a good description of the observables, was deduced from the measured differential-elastic-scattering cross sections. The experimental-results were compared with the respective evaluated quantities given in ENDF/B-V.

I. INTRODUCTION

This report is the fifth in a series dealing with the interaction of fast neutrons with nuclei in the light-fission-product region.[1-4] The objectives of this program are; 1) explicit experimental knowledge of neutron total and scattering cross sections in the light-fission-product region, and 2) the formulation of a "regional" optical-statistical model (OM) suitable for the prediction of the interaction of fast neutrons with experimentally inaccessible light fission products.[5] Elemental niobium is monoisotopic (^{93}Nb), in the region of isomerism just beyond the N = 50 neutron shell[6] and its fission yield is significant (e.g., 6.4% for fission-neutron induced fission of ^{235}U). In the few-MeV region both direct and compound-nucleus (CN) processes are significant. Fluctuations in the CN component are a concern and measurements must be detailed if a determination of the energy-averaged behavior, comparable with OM predictions, is to be reasonably assured. Previous measurements by this group have provided considerable understanding of the neutron total and scattering cross sections of niobium to several MeV.[7,8] That earlier work is now more than a decade old and improved contemporary accuracies lead to better definition of OM parameters. Thus, the measurements were repeated with emphasis on accuracy and energy detail. Broad incident-energy resolutions were used in order to average cross-section fluctuations.

This report briefly outlines the experimental methods (Sec. II), presents the experimental results (Sec. III), interprets and discusses the measured values in terms of the OM (Sec. IV), and compares some of the measured values with evaluated quantities given in ENDF/B-V[9] (Sec. V).

II. EXPERIMENTAL METHODS

The samples were fabricated of high-purity niobium metal. The total-cross-section samples were cylinders 2.5 cm in diameter and 1.25 cm long. They were stacked to thicknesses sufficient to provide neutron transmissions in the range $\approx$ 40 to 60%. The scattering samples were solid cylinders 2.0 cm in diameter and 2.0 cm long. Sample densities were calculated from precise dimension and weight measurements.

The neutron total cross sections were deduced from the observed transmission of monoenergetic neutrons through the samples in the conventional manner.[10] The measurements were made using the rotating-sample technique described in Refs. 11 and 12. The neutron source was the ^{7}Li(p,n)^{7}Be reaction. The neutron-scattering measurements were made using the time-of flight technique and the Argonne ten-angle scattering apparatus.[13] Again, the neutron source was the ^{7}Li(p,n)^{7}Be reaction. Scattered neutrons were detected by proton-recoil scintillators placed at the end of $\approx$ 5.5 m flight paths. All neutron scattering cross sections were determined relative to the neutron total cross sections of carbon[12] in the manner described in Ref. 14. The observed neutron scattering cross sections were corrected for multiple-event, beam-attenuation and angular-resolution effects as described in Ref. 15. Details of the neutron-scattering apparatus and its application are given in Refs. 15-17.

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

The neutron total-cross-section measurements were made from ≈ 0.7 to 4.5 MeV at intervals of ≲ 50 keV with incident-neutron energy spreads of ≈ 50 keV. The incident-neutron-energy scale was known to ≲ 10 keV. The measured energy range was traversed several times, the results combined and the composite data set averaged over 100 keV energy intervals. The statistical uncertainties of the averaged cross-section values were ≈ 1%. The averaged results are shown in Fig. 1. They are in excellent agreement with the low-energy values recently obtained by Poenitz and Whalen.[11] There is reasonable agreement with the results of Ref. 8 above ≈ 1.5 MeV while the present values are 2 to 4% larger at lower energies. The latter differences are consistent with the respective experimental uncertainties.

B. Neutron-Scattering Cross Sections

B.1 Elastic Neutron Scattering

The objective of the elastic-scattering measurements was precise energy-averaged differential-elastic-scattering cross sections. Towards this objective the incident-energy resolutions were intentionally selected to be a relatively broad 50 to 75 keV. These broad incident-energy spreads precluded the experimental resolution of inelastically-scattered neutrons due to the excitation of the 30 keV (1/2-) level.[18] The latter inelastic-neutron group was included with the elastically-scattered component in the measurements and dealt with in the interpretation as discussed below. Measurements were made from 1.45 to 4.0 MeV at intervals of ≈ 50 keV up to 3.0 MeV and at ≈ 200 keV intervals at higher energies. Below ≈ 3.0 MeV the results obtained at adjacent energies were averaged to smooth possible residual fluctuations. The measurements were made at 10 to 20 scattering angles distributed between ≈ 20 and 160 degrees. The angular-scale uncertainty was ≈ 0.5 %. The statistical uncertainties of the measured differential cross sections were generally ≲ 2%. Systematic normalization uncertainties were ≲ 3% and uncertainties due to the correction procedures were ≲ 1%. Thus, the overall uncertainties were generally ≲ 5%.

The measured results are illustrated in Fig. 2. These experimental values were least-squares fitted with a 6^{th}-order Legendre-Polynomial series in order to obtain the angle-integrated "elastic"-scattering cross sections. The results of this fitting procedure are illustrated in Fig. 2 and the resulting angle-integrated "elastic"-scattering cross sections are shown in Fig. 1. The uncertainties of the angle-integrated values are ≈ 5%. Above ≈ 1.8 MeV the present elastic-scattering results are in reasonable agreement with those of Ref. 8, as illustrated in Fig. 1. The present results also reasonably well extrapolate to the lower-energy values of Ref. 7. Representative examples of other previously-reported data are to be found in Ref. 8.

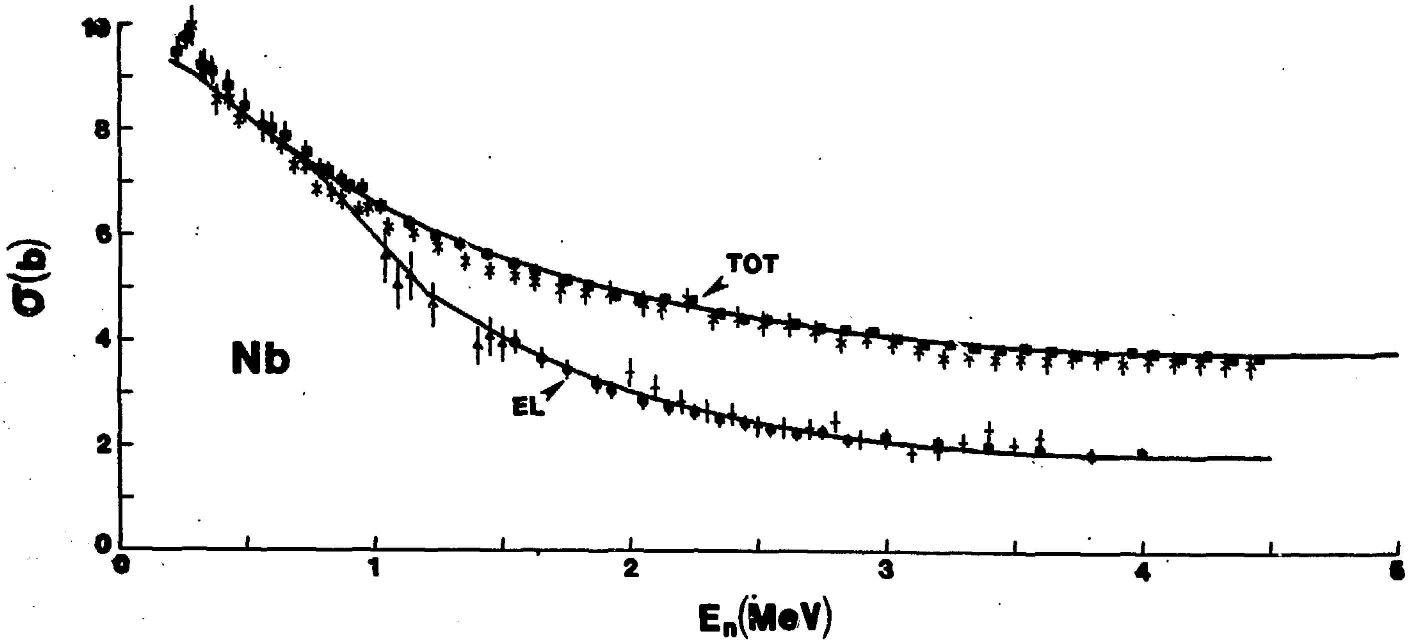

Fig. 1. Neutron Total and Elastic-Scattering Cross Sections of Niobium. Total cross section results are indicated by; ■ = present work, X = 100 keV average of Ref. 8, ◪ = 50 keV average of Ref. 11. Elastic-scattering cross sections by; ■ = present work, △ = Ref. 7 and + = Ref. 8. Curves indicate the results of model calculations.

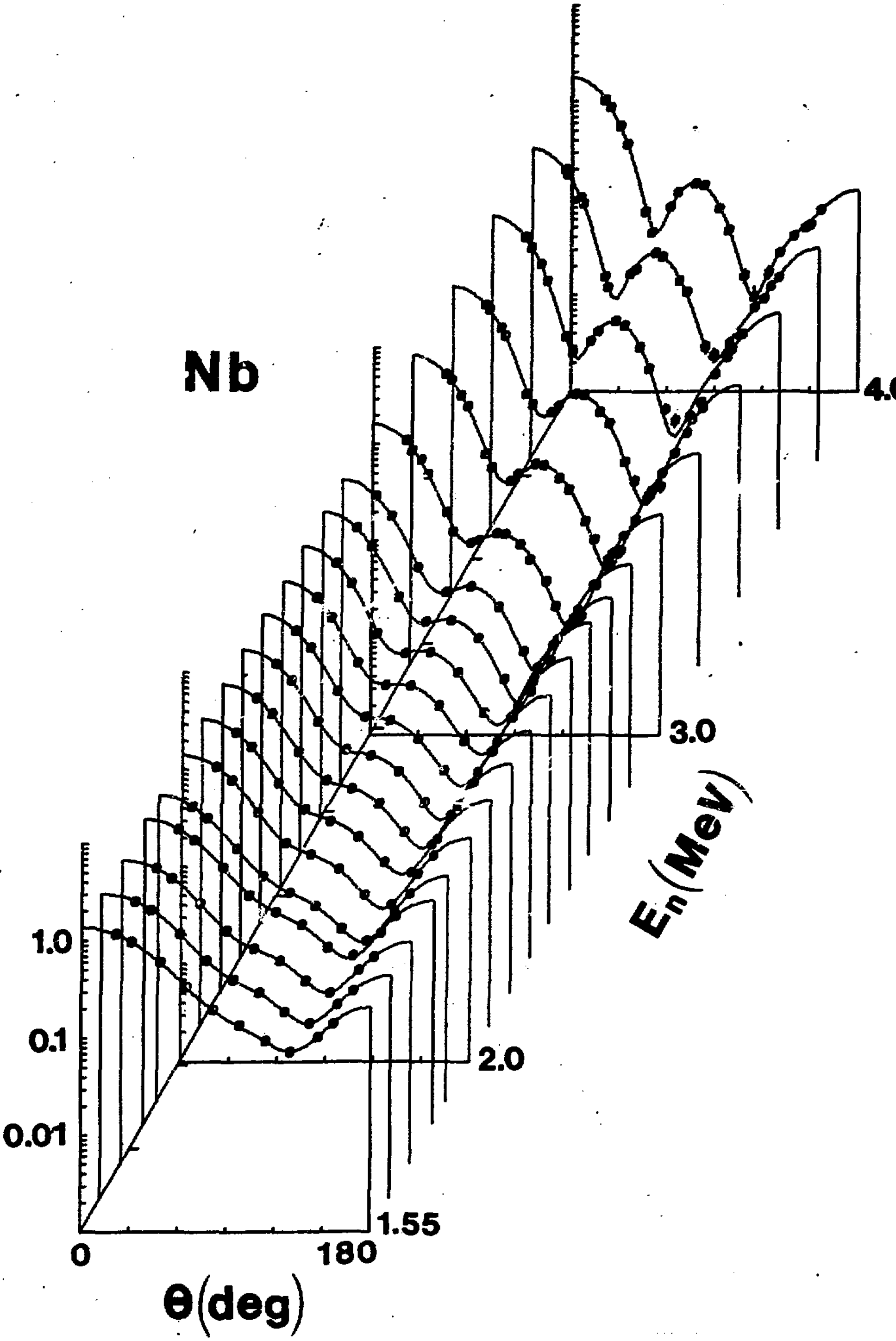

Fig. 2. Differential-Elastic-Scattering Cross Sections of Elemental Niobium. Data points indicate the measured values and curves the results of fitting Legendre-Polynomial series to the experimental quantities. Values are given in the laboratory system.

B.2. Inelastic Neutron Scattering

The broad incident-energy spreads intentionally employed in the measurements precluded the detailed resolution of inelastically-scattered neutron groups (in particular, neutrons due to the excitation of the 30 keV level were included in the observed elastically-scattered neutron group, see above). Despite the experimental limitations, eight-inelastically-scattered neutron groups were firmly identified with two additional, tentatively identified. These observed excitation energies are summarized in Table 1. The cited uncertainties are RMS deviations from the simple averages of the results of a number of measurements. The uncertainties are relevant to mean excitation energies and should not be confused with scattered-neutron resolutions. The observed levels correspond to a number of previously reported niobium levels, as noted in Table 1.[18] The corresponding inelastic-excitation cross sections were determined in the same manner as outlined above for elastic scattering. However, the observed inelastic-neutron angular distributions were nearly isotropic thus the Legendre-Polynomial fits were terminated at the P_2 term. The angle-integrated inelastic-scattering cross sections resulting from the fitting procedures are summarized in Fig. 3. The inelastic-scattering-cross-section uncertainties range from $\approx$ 10% to 30%. Their origins are generally as outlined above for elastic scattering with larger statistical uncertainties. Some of the inelastic-scattering cross sections were corrected for contributions due to the second neutron group from the source reaction and those corrections introduced additional uncertainties. The present inelastic-neutron-excitation cross sections are in good agreement with those previously reported from this laboratory,[7,8] as illustrated in Fig. 3. Ref. 8 cites a number of other previously reported inelastic-scattering cross sections. The present experimental values are internally consistent with the nonelastic cross sections, implied by the measured neutron total and elastic-scattering cross sections, in good agreement with the total inelastic-scattering cross section based upon the sum of the present excitation-cross-sections.

Generally, the prior data base is reasonably represented by ENDF/B-V[9] and comparisons with that evaluation are discussed below.

IV. INTERPRETATION AND DISCUSSION

It was assumed that the present experimental results could be reasonably described by a spherical optical-statistical model (OM).[19] The OM parameters were determined from the measured differential-elastic-scattering distributions with chi-square fitting procedures using the OM program ABAREX[20]. Compound-nucleus contributions (CN) were calculated using the Hauser-Feshbach formula as modified by Moldauer.[21,22] The calculations explicitly treated nine discrete levels up to excitations of 1.07 MeV using the energies and spin-parity values of Ref. 18. Higher-energy excitations were represented using the statistical formalism and parameters of Gilbert and Cameron.[23] The observed "elastic"-scattering cross sections included an inelastic-scattering component due to the excitation of the 30 keV (1/2+) level which was not experimentally resolved from the elastic-scattered neutron group. ABAREX is able to fit composite neutron groups comparable with the observations (in the present application the composite of ground and first-excited state contributions). The observed differential-elastic scattering data of Fig. 2 were concurrently

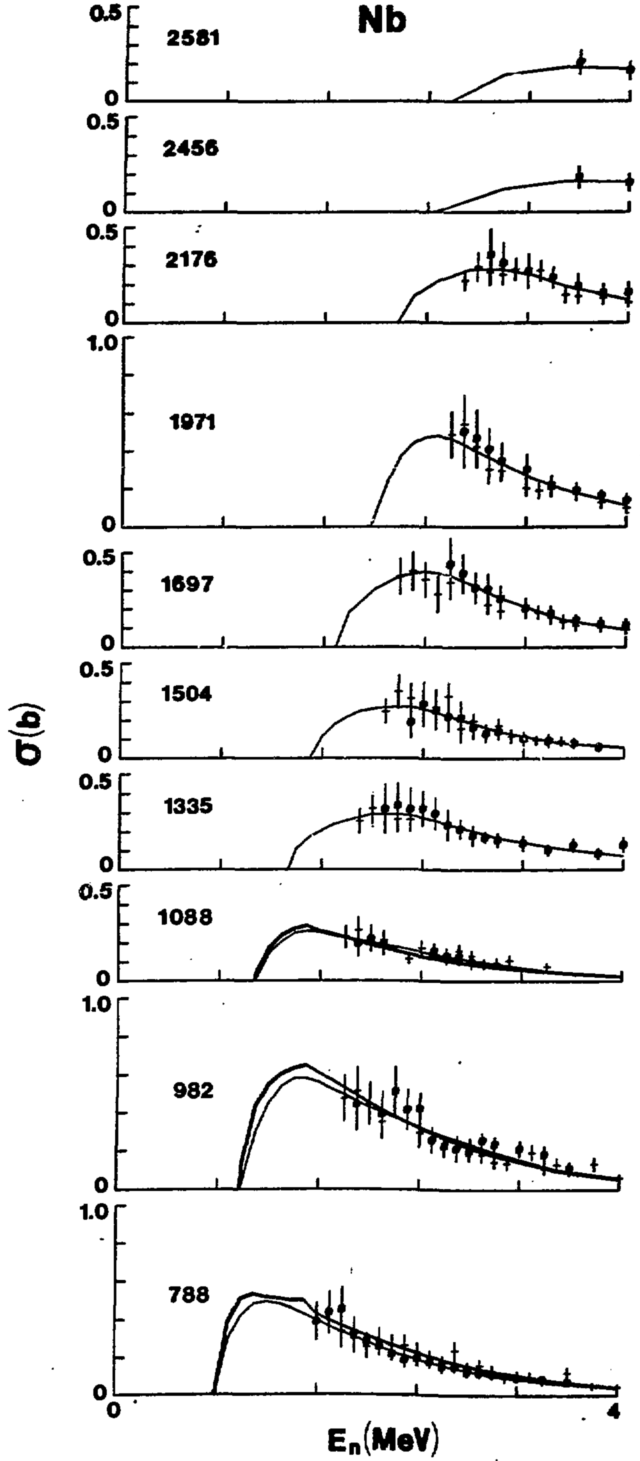

Fig. 3. Inelastic-Scattering Cross Sections of Niobium. The present experimental values are noted by 0 data symbols and those of Ref. 8 by + symbols. Light curves are "eyeguides" constructed through the measured values. Heavy curves denote the results of calculations as described in the text. Observed excitation energies (Table 1) are numerically given in keV in each section of the figure.

fitted by varying the six parameters; real and imaginary, strengths, diffusenesses and radii. It was assumed that the real strength followed an energy dependence of the form $V = V_0 - 0.3 \cdot E$ (MeV) as suggested by global OM studies.[24]

The above fitting procedures resulted in the OM parameters given in Table 2. These parameters are similar to global sets found in the literature; for example the radius of the imaginary potential is larger than that of the real potential.[25] A detailed discussion of this and similar parameter sets will be given in Ref. 5. The parameters of Table 2 provided a good description of the observed differential-"elastic"-scattering cross sections as shown in Fig. 4. They also provide a reasonable description of the observed neutron total and angle-integrated elastic-scattering cross sections as illustrated in Fig. 1; the agreement is generally within the experimental uncertainties. The inelastic-scattering cross sections were calculated for the excitation of levels to 1.062 MeV. These results were combined, as indicated by the correlations of Table 1, to obtain the comparisons with the present experimental results shown in Fig. 3. The calculated results are in reasonable agreement with the measured values extending through the excitation of the reported 1.088 MeV level. Higher-lying levels are too uncertain to permit comparisons of measured and calculated values. The comparisons of Fig. 3 do suggest that the level structure of Ref. 18 is reasonably valid to at least $\approx$ 1.2 MeV and that the statistical parameters of Ref. 23 quantitatively account for channel competition. However, detailed comparisons on a level by level basis are not possible with the present experimental results.

V. COMPARISONS WITH ENDF/B-V

ENDF/B-V[9] is reasonably representative of the data base prior to the present work. The evaluation is documented in Ref. 26. The results of the present measurements are compared with some of the evaluated quantities in Fig. 5. The neutron total cross sections are very similar. The differences between measured and evaluated total cross sections do not exceed 3%, as indicated in Table 3, and are generally only a factor of two or less than the uncertainties associated with the experimental values alone. There are significant differences between measured and evaluated "elastic"-scattering cross sections, particularly over the energy range 1.5 to 2.5 MeV. These, together with the above total cross sections, result in relatively large differences between the evaluated total inelastic-scattering cross sections and the nonelastic cross sections implied by the present measurements. The evaluation treated the elastic-scattering cross sections as the difference between the other partial cross sections and the total cross sections. That procedure is not justified with the relatively well known "elastic"-scattering cross sections of the present work. The scattered-neutron resolution of the present measurements was not sufficient to permit an effective level-by-level comparison with the individual evaluated inelastic-excitation cross sections. However, the above noted discrepancy between the experimentally based nonelastic cross sections and the evaluated total inelastic-scattering cross sections suggests that the sum of the evaluated inelastic-excitation cross sections is too large by 10% to 15% from 1.5 to 2.5 MeV. Such a systematic discrepancy can occur when summing a number of small and relatively uncertain components.

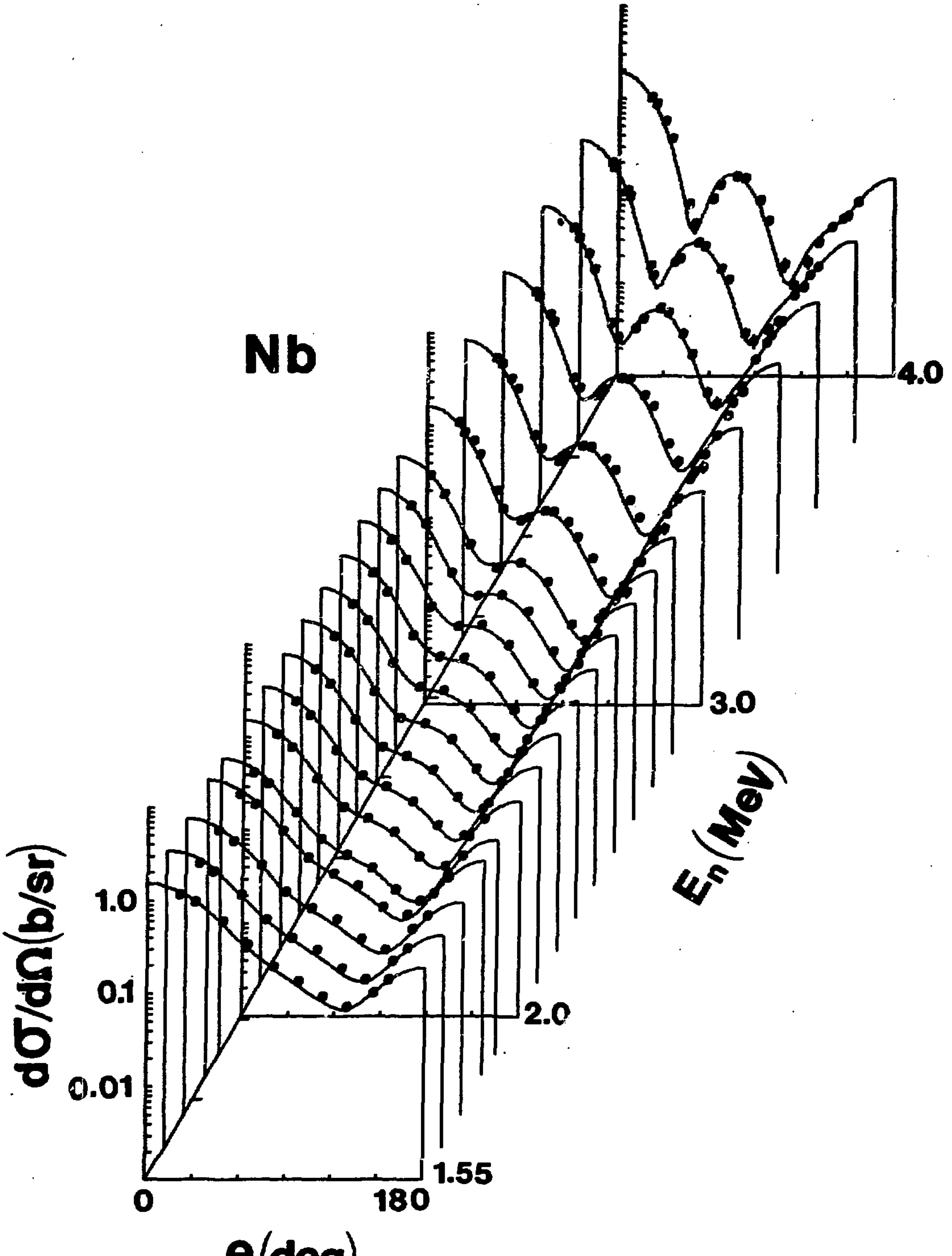

Fig. 4. Comparison of the Present Measured (Data Points) and Calculated (Curves) Neutron-Differential-Elastic-Scattering Cross Sections of Elemental Niobium. Values given in the laboratory system.

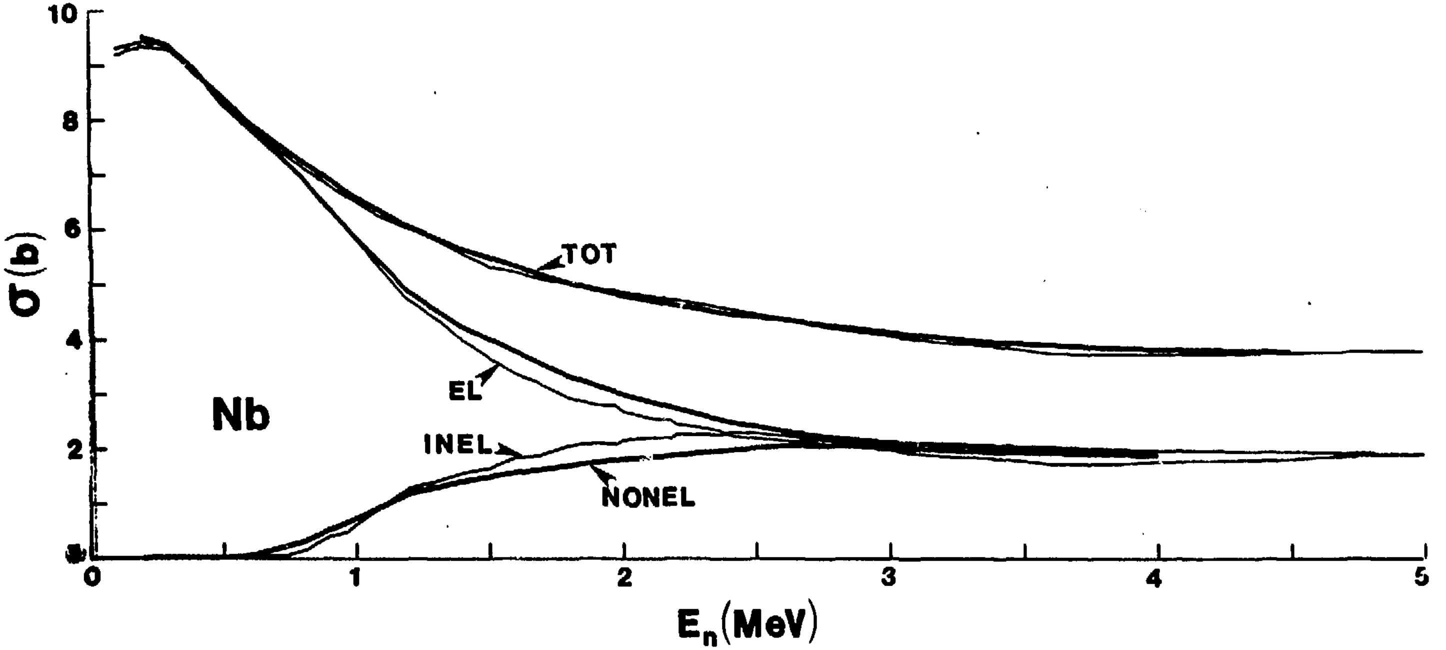

Fig. 5. Comparison of Measured and Evaluated Neutron Total, Elastic-Scattering and Nonelastic and Inelastic-Scattering Cross Sections of Niobium. Heavy Curves indicate the present experimental results and light curves ENDF/B-V values.

VI. SUMMARY COMMENTS

The present experiments give new definition to neutron total cross sections of niobium from ≈ 1.0 to 4.5 MeV and to elastic-scattering cross sections from ≈ 1.5 to 4.0 MeV. They also define broad-group inelastic-scattering cross sections to excitations of ≳ 2.0 MeV. These experimental results are in reasonable agreement with values previously reported from this laboratory[8]. Some discrepancy with values given in ENDF/B-V was noted. The measured elastic-scattering results were used to derive the parameters of a spherical OM. This model gave a good description of the experimental observables. The model parameters provide an input to the formulation of a "regional" OM suitable for use in the light fission-product region.[5]

ACKNOWLEDGEMENTS

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TABLE 1. Observed Excitation in Elemental Niobium

No.	E_x(keV)	Previously Reported Values (keV)[18]
1	788 ± 23[a]	687(3/2-), 744(7/2+), 808(5/2+), 810(3/2-)
2	982 ± 17	950(13/2+), 979(11/2+)
3	1088 ± 27	1082(9/2+)
4	1335 ± 35	1290, 1297, 1315, 1334, 1364, 1369, 1395
5	1504 ± 30	1483, 1491, 1499
6	1697 ± 19	1572, 1603, 1666, 1680, 1683, 1688, 1710, 1775
7	1971 ± 22	1910, 1915, 1947, 1949, 1966, 2001
8	2176 ± (?)[b]	2117, 2153, 2171, 2180, 2203
9	(2456)[c]	
10	(2581)[c]	

[a] Uncertainties are defined as the RMS deviation from the simple average of a number of observations.

[b] Insufficient data for establishing quantitative uncertainties.

[c] Tentative assignments.

Table 2. Optical-Model Parameters

Real Potential[a]			
Strength[c]	V_o	=	49.714 MeV
Radius[b]	r_v	=	1.230 F
Diffuseness	a_v	=	0.702 F
$V_o r_v^2$		=	75.25 MeV-F^2
J/A_v		=	448.54 MeV-F^3
Imaginary Potential[c]			
Strength	W	=	6.505 MeV
Radius	r_w	=	1.349 F
Diffuseness	a_w	=	0.477 F
Wa_w		=	3.102 MeV x F
J/A_w		=	63.89 MeV x F^3

[a]Assume; 1) energy dependence V = Vo - 0.3 · E(MeV), 2) Saxon form, and 3) spin-orbit term of Thomas form with 6 MeV strength.

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

[c]Saxon derivative form.

Table 3. Comparison of Measured and Evaluated Neutron Total and Elastic-Scattering Cross Sections of Niobium

	$\frac{\text{ENDF-EXP}}{\text{EXP}}$	
E_n (MeV)	Totals	Elastics
1.0	-1%	0%
1.5	-2.5%	-8%
2.0	+2.0%	-9.6%
2.5	+1.5%	-8.6%
3.0	-0.5%	-3.3%
3.5	-2.9%	-4.1%
4.0	-2.7%	-3.5%
4.5	0%	-