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ANL/NDM-54

The Nonelastic-Scattering Cross Sections of Elemental Nickel

by

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

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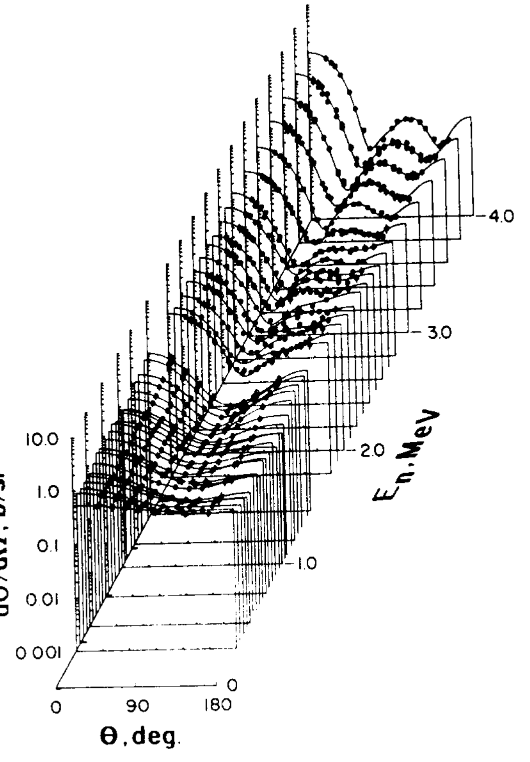

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THE NONELASTIC-SCATTERING CROSS SECTIONS OF ELEMENTAL NICKEL*

by

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ABSTRACT

Neutron total cross sections of elemental nickel are measured from 1.3 to 4.5 MeV, at intervals of ~50 keV, with resolutions of 30-50 keV and to accuracies of 1-2.5%. Neutron differential-elastic-scattering cross sections are measured from 1.45 to 3.8 MeV, at intervals and with resolutions comparable to those of the total cross sections, and to accuracies of 3-5%. The nonelastic-scattering cross section is derived from the measured values to accuracies of $\gtrsim$6%. The experimental results are compared with previously reported values as represented by ENDF/B-V and areas of consistency and discrepancy noted. The measured results are shown to be in good agreement with the predictions of a model previously reported by the authors.

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

I. INTRODUCTION

Nickel is a major constituent of stainless steel. As such the neutron cross sections of elemental nickel are of considerable interest, particularly those associated with inelastic-scattering processes (1). There have been a number of studies of inelastic neutron scattering from elemental nickel the results of which are not always consistent. Some are perturbed by cross section fluctuations and only a few approach the desired cross section accuracy goals (2,3,4,5,6). In the few-MeV region the neutron inelastic-scattering cross section of nickel approaches the nonelastic-scattering cross section with the remaining contributions being due to relatively small and well known reaction cross sections (2). Thus a careful determination of the nonelastic-scattering cross section gives good guidance as to the neutron inelastic-scattering cross section. The nonelastic-scattering cross section can, obviously, be derived in a straight forward manner from the measured neutron total and elastic-scattering cross section. The latter two cross sections of nickel are significantly different in the few MeV range and their careful measurement can imply a nonelastic-scattering cross section to good accuracies. However, there are questions as to the general accuracies of neutron total cross sections in the fluctuating energy region of interest (7). There are also questions as to the appropriateness of models for the description of neutron cross sections in the mass-energy region of the present work (8). It was the limited objective of this work to determine the neutron total and elastic-scattering cross sections of elemental nickel in the few-Mev region to accuracies that would give improved definition to the nonelastic-scattering cross section (and thus the inelastic-scattering cross section) of elemental nickel, to better define the energy-average magnitudes of neutron total and elastic-scattering cross sections, and to provide a reasonable test of calculational models.

II. EXPERIMENTAL METHODS

The present measurements generally employed the instrumentation, measurement techniques and data handling procedures long used at the Argonne Fast Neutron Generator. They have been extensively defined in a number of publications, recently in the context of similar measurements of neutron total and scattering cross sections of ^{60}Ni as described in Ref. 8.

The only change from the above established procedures involved the normalization of the neutron elastic-scattering measurements. Since the primary objective of the present work was the precise measurement of neutron elastic-scattering cross sections, considerable attention was given to the calibration of the ten neutron time-of-flight detectors employed in the elastic-scattering measurements. The relative energy sensitivity of each of these detectors was established by the observation of prompt-fission neutrons emitted at the spontaneous fission of ^{252}Cf in the manner described in Ref. 9. These ten detector sensitivities were then normalized to a common relative value by observing neutrons emitted from the neutron source at a zero-degree reaction angle at selected neutron energies over the range of interest. This procedure resulted in detector balance factors with a consistency of ~2%. In addition, carbon elastic-scattering angular distributions were used to verify the absolute angular scale of the measurement system as, at some energies (e.g. 3.3-3.6 MeV), differential scattered-neutron distributions from carbon display very pronounced and well-known angular-dependent structure (10). Finally, the relative sensitivity of the detection system was placed on an absolute scale using the well known neutron total cross sections of elemental carbon (10). In the energy range of interest the carbon neutron total and elastic-scattering cross sections are essentially identical. Relative differential elastic-scattering distributions from carbon were measured at ten or more angles and at a number of energies selected to avoid resonance structure in the carbon cross section. These relative distributions were fitted with Legendre Polynomial expansions, as outline below, and the sensitivity of the detection system adjusted to bring the angle-integrated elastic scattering cross sections into agreement with the neutron total cross section of Ref. 10. The normalization factors obtained at a number of incident energies were averaged to obtain a mean value which was then used throughout a measurement sequence.

The above procedures involved a number of judgments that make it difficult to explicitly quantify uncertainties. Some guidelines as to the calibration uncertainties are: carbon measurement uncertainties $\lesssim 3\%$, uncertainties attributable to the carbon reference standard $\lesssim 2\%$, and uncertainties associated with the relative ^{252}Cf measurements $\lesssim 3\%$. These estimates imply an overall normalization uncertainty of 3-5%. The approach is reasonably free of some of the well known problems associated with use of the H(n;n) reaction as a reference standard; e.g. notably the large energy transfer in hydrogen scattering. The method does imply neutron elastic scattering cross sections relative to the neutron total cross section of elemental carbon.

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

The measurements were made with resolutions of 30-50 keV, at incident energy intervals of ~50 keV from 1.3 to 4.5 MeV. Three independent sets of measurements were made, each involving a wide range of nickel-sample thicknesses and several carbon reference samples. An illustrative set of samples consisted of three nickel samples (0.668, 2.000 and 3.683 cm. in thickness) and three carbon samples (1.0, 2.0 and 3.0 cm. in thickness). All nickel samples were fabricated into 2.5 cm diameter cylinders from high-purity metal and arranged so that the neutron transmission was parallel to the cylinder axis. The carbon samples were fabricated of pile-grade graphite into similar cylinderical geometries. The samples in each set of measurements were arranged so as to provide a number of neutron transmissions extending over the range ~35-85%. The respective neutron total cross sections were deduced from the observed transmission of the pseudo-monoenergetic neutron beam through the measurement sample in the conventional manner (11). The resulting cross sections fluctuated with energy reflecting the underlying resonance structure in the context of the experimental energy resolution. The cross sections were also sensitive to the sample size with those obtained from the thicker samples being systematically smaller than those obtained with the thinner samples at the lower measurement energies where the underlying resonance structure is more pronounced. At each measurement energy the experimental results were extrapolated to the infinitely-thin-sample limit assuming a linear dependence of cross section on sample thickness. Such a behavior was consistent with experimental observation and, in this case, a good approximation of theoretically estimated correction factors (12). Errors in this simple approximation will tend to be reflected in too low final cross-section results. The magnitude of the sample-size-correction factor varied from 5-15% at the lowest measured energies to essentially zero at the upper measured energies in a generally systematic energy-dependent manner. The results, corrected to the infinitely-thin-sample limit, were averaged over 200 keV intervals using a "running average" procedure in order to smooth fluctuations due to the underlying structure. Each averaged value contained 15-20 individual quantities. The statistical accuracies of the individual measured cross sections were 1-2% and the statistical accuracies of the averaged values were far better. Systematic uncertainties due to the experimental procedures were believed to be ~1% and those due to the correction to the infinitely-thin-sample limit ~1-2%. Thus the overall accuracies of the energy-averaged-cross-section values was believed to be in the range 1-2.5%. The energy-averaged results, shown in Fig. 1, were generally consistent within the above uncertainty estimates. The energy-dependent behavior is relatively smooth with some residual fluctuations not fully removed with the 200 keV averaging increment. Their magnitude is generally considerably less than 5%.

Concurrent with the above nickel measurements the neutron total cross sections of elemental carbon were obtained using identical procedures. The results generally agreed with recognized reference values to within 1-2% (10).

B. Neutron Differential-Elastic Scattering

The neutron differential-elastic-scattering cross sections were measured at ten scattering angles distributed between ~20 and 160 deg., from 1.45 to 3.8 MeV, at intervals of ~50 keV and with incident-neutron energy resolutions of 50-100 keV. The experimental scattered-neutron resolution was sufficient to resolve the elastically-scattered component from all known inelastically-scattered contributions. The statistical accuracies of the individual data points were several percent or better. All of the measured results were corrected for multiple events, incident-beam attenuation and angular resolution effects in the manner outlined in Ref. 14. The uncertainties associated with these correction procedures were estimated to be 1-2%. Thus the over all experimental uncertainty was dominated by the 3-5% uncertainties associated with the normalization procedures outlined above.

The experimental results were least-square fitted with Legendre Polynomial expansions of the form

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}\left\{1 + \sum_{n=1}^{6} W_n\ P_n\right\} \tag{1}$$

in order to obtain the angle-integrated neutron elastic-scattering cross sections. The primary experimental results are outlined in Fig. 2. Despite the relatively broad experimental resolutions, it is clear that these distributions fluctuate with energy and angle. These fluctuations were largely removed by constructing a "running" 200 keV average of the measured values comparable to that employed in the reduction of the neutron total cross sections, above. The averaged results behaved in an energy-smooth manner as illustrated in Fig. 3. Again, the energy-averaged differential values were fitted with the Legendre expansion of Eq. 1 to obtain the averaged angle-integrated elastic-scattering cross sections. The results of the fitting procedure were descriptive of the average of the measured distributions as illustrated in Fig. 3. The corresponding angle-integrated elastic-scattering cross sections are shown in Fig. 1. They are believed known to 3-5%. This uncertainty is essentially entirely attributable to the normalization procedures outlined above.

Concurrently with the above nickel measurements, relative neutron differential-elastic-scattering distributions of carbon were measured. The results were very consistent with the accepted values given in Ref. 10.

IV. DISCUSSION

The present neutron total-cross-section results are in very good agreement with the comparable energy-averaged of values constructed from ENDF/B-V (13) above 3.5 MeV. However, the present results become progressively larger than the evaluation as the energy decreases, amounting to a 12-14% discrepancy at ~1.5 MeV. These general trends are illustrated in Fig. 1 and are far beyond effects that can reasonably be attributed to residual fluctuations. Similar trends are reflected in the comparison of measured and evaluated neutron elastic-scattering cross sections (see Fig. 1). Such total-cross-section discrepancies were relatively common in this mass-energy region and have been attributed to resonance self-shielding perturbation of the experimental measurements (8,14). Many of the previous measurements of nickel total cross sections have employed relatively thick samples (e.g. ~3.5 cm and nickel has a very high atomic density (16)). Though the experimental resolutions were good, they were not sufficient to resolve all of the resonance structure in the few-MeV region. As a consequence, self-shielding perturbations were present to a varying extent. Such perturbations may well be the origin of the above discrepancy. It should be again noted that the present measurements always included carbon reference samples and that the resulting neutron total cross sections of carbon were consistent with the accepted values to within 1-2%. The evaluation of Ref. 13 generally results in lower total-cross-section values below 3.0 MeV than all of the thin-sample results of the present work even without correction factors. In addition, the present elastic-scattering results are largely independent of the total-cross-section values and generally subject to different correction factors. At lower energies the present elastic-scattering values approach the evaluated neutron total cross section of Ref. 13 in a region where there is known to be an appreciable nonelastic cross section; again a discrepant situation.

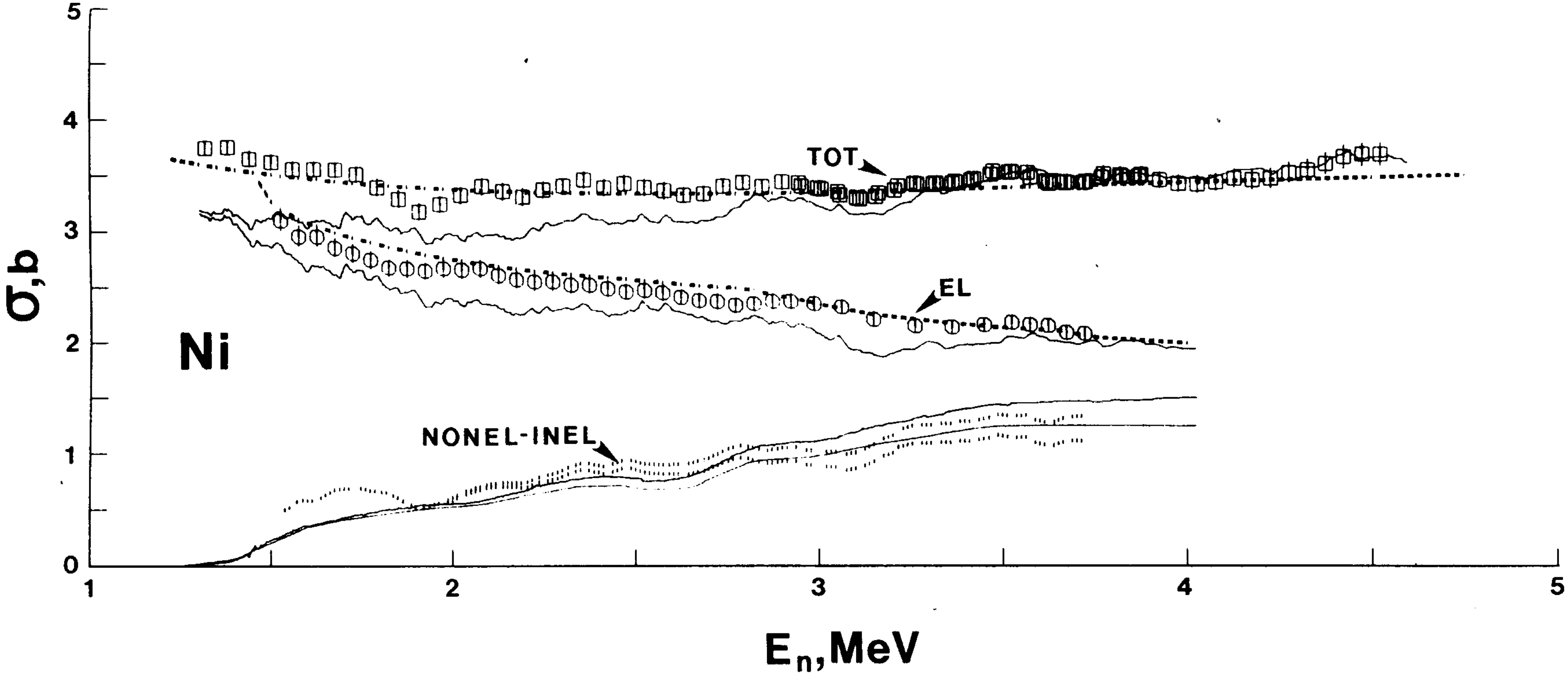

Fig. 1. Neutron cross sections of elemental nickel, The present experimental results are indicated by data symbols: squares for total cross sections and circles for angle-integrated elastic-scattering cross sections. The dashed curves indicate neutron total and elastic-scattering cross sections calculated with the model of Ref. 8. The dotted curves indicate the non-elastic (upper) and total inelastic-scattering cross sections (lower) implied by the present measurements. Solid curves indicate the respective cross sections taken from ENDF/B-V (13). All cross sections have been averaged over a 200 keV energy interval.

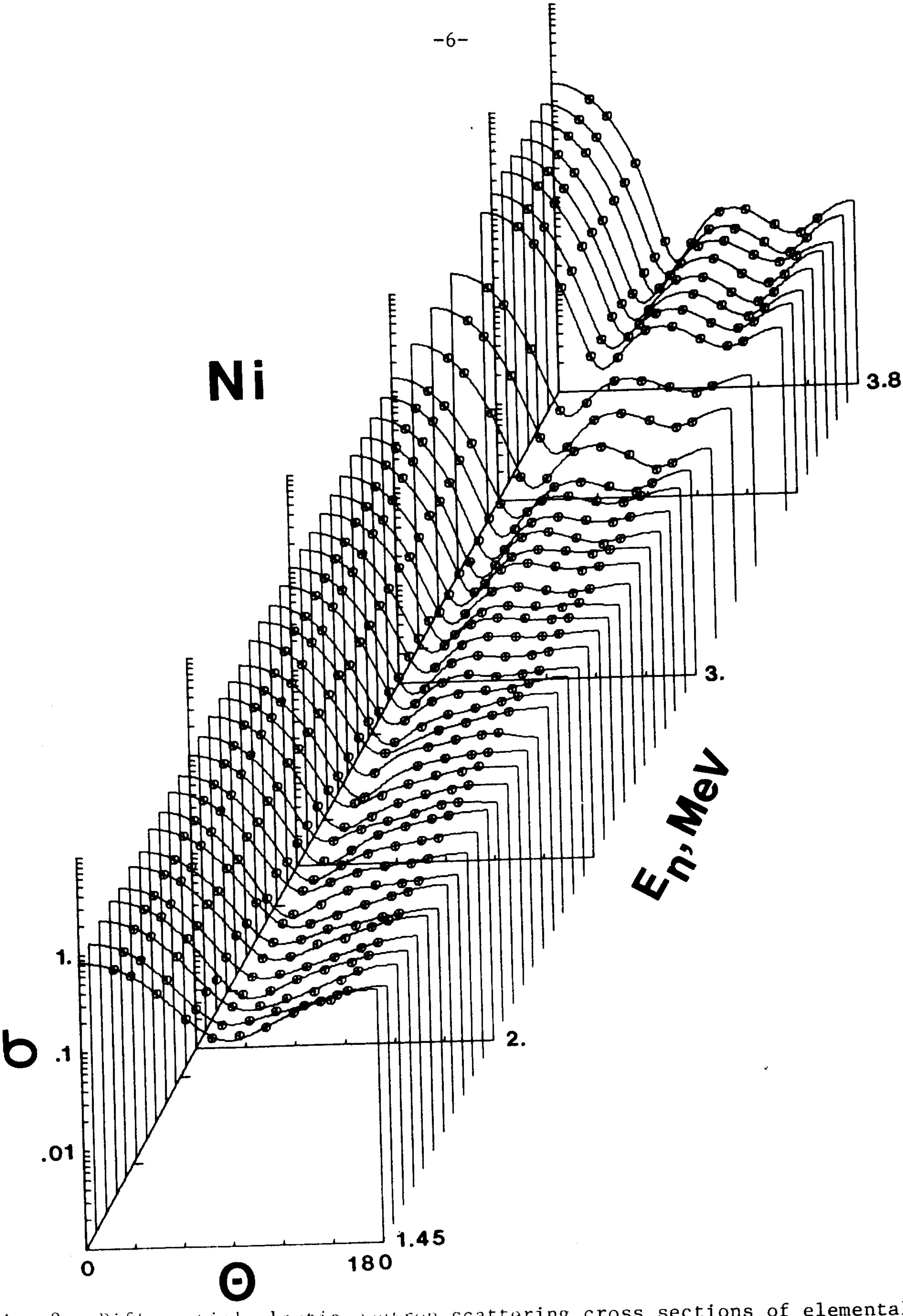

Fig. 2. Differential elastic neutron scattering cross sections of elemental nickel. The present experimental results are indicated by data points. Curves show the results of fitting Eq. 1 to the measured values. The dimensionality is differential cross section in b/sr and scattering angle in lab. deg.

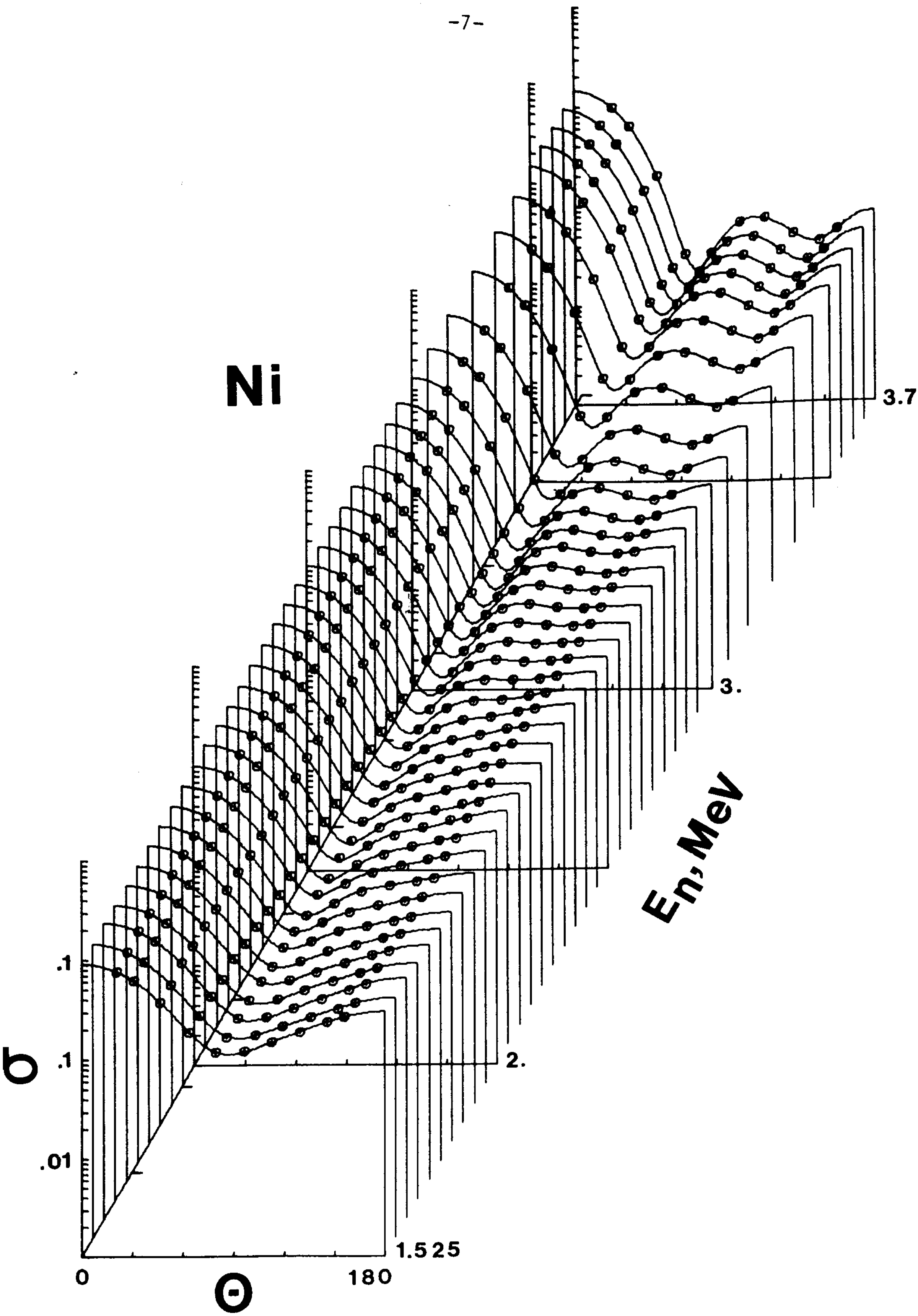

Fig. 3. Differential elastic neutron scattering cross sections of elemental nickel. 200 keV averages of the present experimental results are indicated by the data points. Curves denote the results of fitting Eq. 1 to the averaged values. The dimensionality is differential cross section in b/sr and scattering angle in lab. deg.

The nonelastic-scattering cross section follows directly from the present measurements with the results as shown in Fig. 1. Small corrections for minor reaction cross sections were made using ENDF/B-V in order to obtain the neutron total-inelastic-scattering cross section also shown in Fig. 1. For comparison, similar energy-averaged values constructed from ENDF/B-V are shown in the figure. Generally, the inelastic-scattering cross section implied by the present measurements is somewhat smaller than that of the evaluation at higher energies. There is an opposite trend at lower energies but the implications of the present measurements become more uncertain as the energy decreases. A more quantitative comparison of the present implied inelastic-scattering cross sections and those given by evaluations is shown in Table I. The uncertainties associated with the present implied inelastic-scattering cross section range upward from ~6% depending upon the difference between neutron total and elastic-scattering cross sections and the assumed accuracy of the present elastic-scattering results. The present implied inelastic scattering results are consistent with those given in an evaluation previously reported by some of the present authors (2). That is not so true of ENDF/B-V, particularly at higher energies where the present interpretation is most reliable, since it tends to give inelastic-scattering cross sections 8-10% larger than suggested by the present measurements at energies of ~3-4 MeV. Recent gamma-ray production results (3) similarly suggest that ENDF/B-V is too large in the comparable energy range by even larger amounts. The implications of the present work lead to inelastic-scattering cross sections approximately midway between the values given in ENDF/B-V and in Ref. 3.

It has been frequently observed that optical potentials based upon several-MeV neutron differential elastic-scattering cross sections in this mass region over predict the neutron total cross sections in the vicinity of 1 MeV. This was particularly noted in the instance of ^{60}Ni discussed in Ref. 8. In that reference it was suggested that the discrepancy was due to the above self-shielding perturbation of the total-cross-section measurements. In the particular case of ^{60}Ni a rare sample was involved and thus it was impossible to experimentally test the validity of that suggestion. Such tests were a part of the present complimentary measurements involving the readily available elemental nickel.

The optical potential of Ref. 8 was explicitly used to calculate the neutron total and elastic-scattering cross sections of elemental nickel. The calculated total and angle-integrated elastic-scattering cross sections are compared with the present experimental results in Fig. 1. The agreement between measurement and calculation is very good, with the small discrepancies easily attributable to residual fluctuations. Similarly, the calculated differential-elastic-scattering distributions are descriptive of the observed values as illustrated in Fig. 4. It must be emphasized that these calculations explicitly employed the potential of Ref. 8 with no parameter adjustments. It was concluded that many of the difficulties encountered in the model interpretation of neutron processes in the mass-energy range of the present study are of an experimental origin, rooted in the inappropriate or nonexistent treatment of resonance self-shielding effects.

Table I. Implied neutron total inelastic-scattering cross sections.[a]

E_n, MeV	Exp.,[c]	Eval.,[d] (Ref. 2)	Eval.,[b] (ENDF/B-V)[d]
1.525[b]	0.495 ±0.156 ±0.098	0.300	0.270
2.00	0.602 ±0.135 ±0.087	0.599	0.559
2.50	0.867 ±0.128 ±0.078	0.763	0.706
3.00	0.906 ±0.122 ±0.078	0.970	1.007
3.50	1.165 ±0.113 ±0.073	1.180	1.271
3.70	1.127 ±0.109 ±0.071	1.176	1.275

[a]Assuming (n;p) and (n;alpha) cross sections as given in ENDF/B-V.

[b]Not significant due to fluctuations very near threshold.

[c]The two uncertainties correspond to ±5% and ±3% error on the angle integrated elastic scattering cross sections. The error in the total cross section is taken as ±1%.

[d]200 keV average of evaluated quantities.

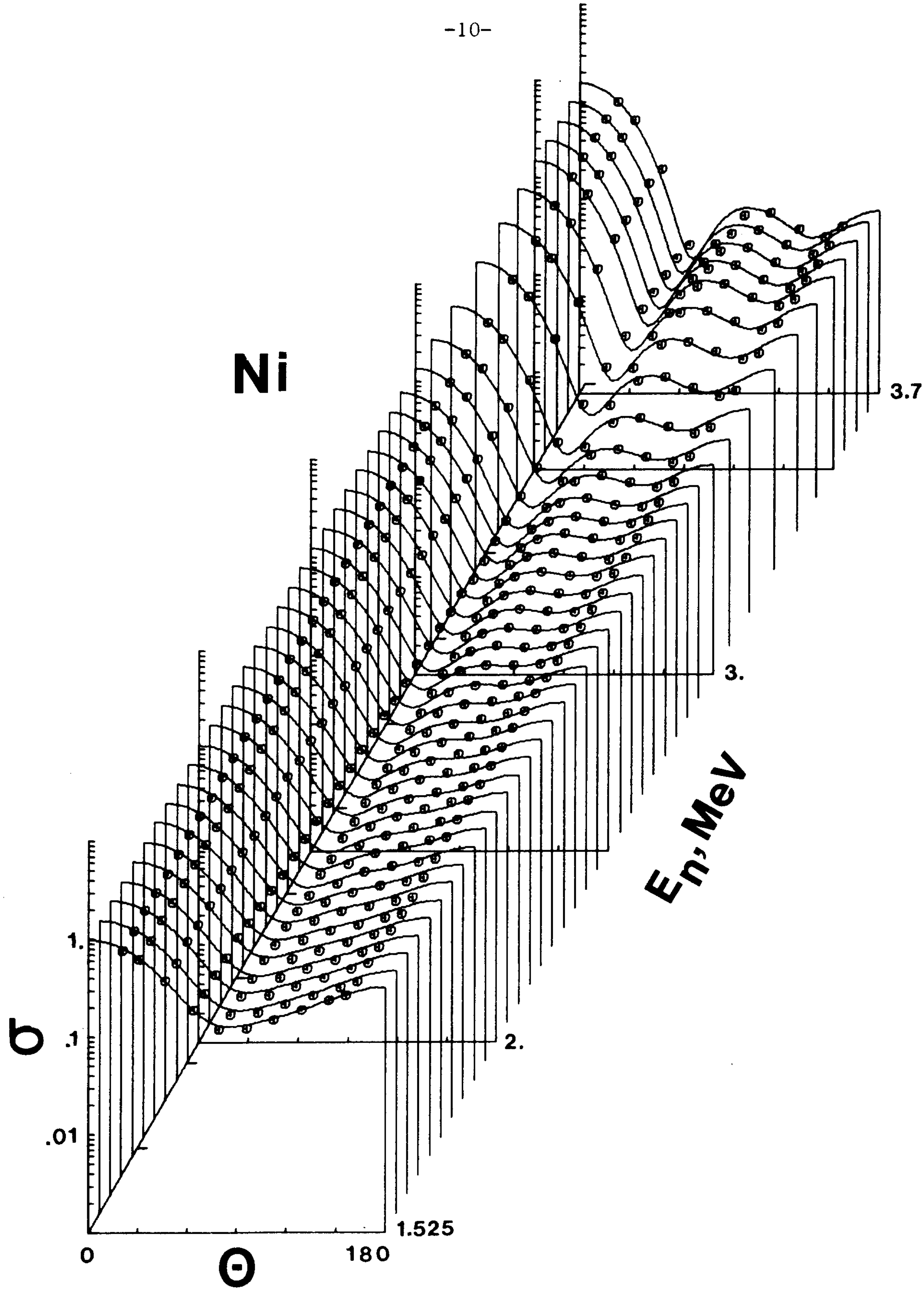

Fig. 4. Comparison of measured and calculated differential neutron elastic-scattering cross sections of elemental nickel. 200 keV averages of the present experimental results are indicated by data points. The curves denote the results of model calculations as defined in the text. The dimensionality is differential cross section in b/sr and scattering angle in lab. deg.

V. CONCLUDING REMARK

The above measurements and calculations suggest that many of the problems previously experienced with neutron cross section in this mass-energy range are in part due to the omission of appropriate consideration of self-shielding effects in simple transmission measurements in an un-resolved or partly resolved resonance region. Similar problems are significant in other mass-energy contexts (12).

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