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ANL/NDM-43

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A.B. Smith, R. Holt, and J. Whalen

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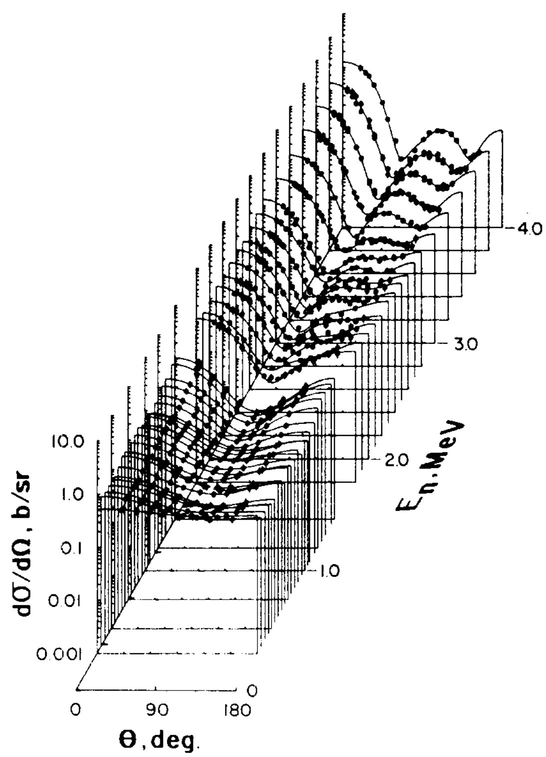

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NUCLEAR DATA AND MEASUREMENTS SERIES

The Nuclear Data and Measurements Series presents results of studies in the field of microscopic nuclear data. The primary objective is the dissemination of information in the comprehensive form required for nuclear technology applications. This Series is devoted to: a) measured microscopic nuclear parameters, b) experimental techniques and facilities employed in measurements, c) the analysis, correlation and interpretation of nuclear data, and d) the evaluation of nuclear data. Contributions to this Series are reviewed to assure technical competence and, unless otherwise stated, the contents can be formally referenced. This Series does not supplant formal journal publication but it does provide the more extensive information required for technological applications (e.g., tabulated numerical data) in a timely manner.

TABLE OF CONTENTS

NEUTRON SCATTERING FROM ^{12}C IN THE FEW-MEV REGION

by

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ABSTRACT

Neutron total cross sections of natural carbon are deduced from the observed transmission of approximately monoenergetic neutrons through carbon samples of varying thickness. The measurements extend from $\sim$0.1 to 4.5 MeV with resolutions of $\sim$2 to 100 keV. Neutron differential-elastic-scattering cross sections of natural carbon are measured from 1.5 to 4.0 MeV at incident-neutron energy intervals of $\lesssim$100 keV, over an angular range of $\sim$20 to 160 degrees and with energy resolutions of 20 to 50 keV. The experimental results are interpreted in terms of a multilevel R-function analysis. Results are compared with the large body of measured and evaluated neutron total and scattering cross sections and scattered neutron polarizations reported in the literature. The present work suggests that the observed neutron total and scattering cross sections of carbon are physically consistent and suitable for use as a reference standard in experimental studies of neutron processes. The R-function description should provide a convenient description of neutron total and scattering cross sections of carbon as a function of both angle and energy.

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

I. INTRODUCTION

Over a number of years neutron total and scattering cross sections of carbo have routinely been determined at the Argonne Fast Neutron Generator in order to verify the consistency of the measurement systems. These ancillary results have accumulated to form a large data base which is routinely reviewed in an effort to improve the knowledge of carbon reference cross sections. Such cross sections constitute a useful secondary-reference standard in many measurement applications as they are often far easier to handle in the experimental environment than the primary H(n,n) reaction. This review is the second such summary, the first being given in Ref. 1. It is expected that subsequent reviews based upon the increasing data base will lead to a continuing improvement in these carbon reference cross sections.

Subsequent portions of this paper outline the experimental methods employed in the present measurements (Sec. II), compare the present experimental results with other reported measured and evaluated data sets (Sec. III), and describe an R-function interpretation of the present experimental values (Sec. IV). The latter provides a physically sound mechanism for the interpolation of measured values in both angle and energy.

II. EXPERIMENTAL METHODS

A. Broad-resolution Transmission Measurements

The neutron total cross sections were determined from the transmission of neutrons through carbon samples of varying thicknesses. The objective was accurate energy-averaged total-cross-section magnitudes, not the precise determination of energy scales or optimum resolution of structure.

All samples were cylinders of pile-grade graphite whose lengths were varied to provide transmissions in the range $\approx$25-75 percent. The radii of the samples were ∿2–2.5 cm. Sample density was determined by precision weighing and dimensional measurement. Heating and/or vacuum-pumping tests indicated no significant absorbed contaminants such as oil or water. The samples were fabricated over an extended period of time using various stock material with no apparent sample-dependent effect on the experimental results.

The total cross section measurements were made using the computer-controlled measurement apparatus at the Argonne Fast Neutron Generator.[2] Nano-second bursts of approximately monoenergetic neutrons were obtained using the ^{7}Li(p;n)^{7}Be reaction.[3] Metallic lithium targets were fabricated by vacuum evaporation with thicknesses adjusted to provide incident neutron energy spreads at the transmission samples of ∿2–100 keV as referenced to the reaction threshold energy. The neutron source was surrounded by a large shield containing a 1 m long 1 cm diameter collimator at the zero-degree source-reaction angle. The samples were fixed to a wheel located ∿10 cm from the collimator exit. The wheel was rotated in a stepping motion in order to place samples and voids alternately in the beam for periods of ∿0.5 sec. The sample and void positions were correlated with data storage using an on-line digital computer. Thus source-intensity monitoring was not required. The neutron detector consisted of a hydrogenous scintillator placed a few meters from the sample wheel on the beam axis. Conventional time-of-flight techniques were used to record the velocity spectrum of neutrons arriving at the detector. The neutron flight paths varied from 5 to 7 m. The prominent spectrum peak due to the primary ^{7}Li(p;n)^{7}Be neutron group was integrated and corrected for small background effects as deduced from regions on either side of the peak. Sample transmissions and associated uncertainties were continuously calculated in real-time and the measurements were continued until a predetermined statistical accuracy of ∿1% was achieved. Total cross sections were deduced from the measured transmissions in the conventional manner. Attention was given to experimental perturbations. A real-time clock was inserted into the detection system in order to precisely determine small dead-time corrections and these were verified by changing source intensities by up to a factor of five. Calculations indicated that in-scattering effects were negligible and this was supported by the consistency of results obtained with a range of sample dimensions.

The energy scale was determined to within $\sim$2-8 keV by control of the incident proton energy. These energies were substantiated by concurrent measurements of well-known resonances in silicon and sulfur.[4,5] Energy-scale uncertainties did not significantly affect the carbon cross section results in wide regions away from the few sharp resonances. The primary objective remained the precise determination of energy-averaged cross section magnitudes. Precise resonance energies have been better measured elsewhere.[6,7]

B. Differential Elastic Scattering Measurements

The differential elastic scattering measurements were made over a seven-year period during which carbon-scattering cross sections were routinely determined in order to verify the performance of the apparatus in a variety of other scattering measurements. The results, collected and summarized herein, were obtained using a number of permutations of the same basic time-of-flight system at the Argonne Fast Neutron Generator.[8] To an appreciable extent, the reproducibility of the results obtained with varying experimental arrangements is indicative of the actual uncertainties of the results.

The $^{7}Li(p;n)^{7}Be$ reaction was used as a neutron source throughout these measurements. The incident-neutron energy spreads varied from $\sim$20 to 50 keV and the incident-neutron energy scale was known to $\sim$10 keV. Generally, the incident-neutron energy spread was smaller at higher energies. The neutron-source intensity was monitored with a secondary time-of-flight proton-recoil-scintillation detector positioned so that only neutrons from the $^{7}Li(p,n)$ source were observed. In addition, several long counters were arranged to serve as secondary source monitors. Uncertainties associated with monitoring the source intensity were generally small, e.g. $\leq$1 percent.

The scattered neutron measurements were made at ten or more scattering angles distributed between $\sim$20 and 160 deg. The relative angular displacement of the detectors was optically determined to within <0.5 deg. The zero-angle calibration of the angle system was determined to within <1.0 deg. by observing the energy loss in the H(n;n) scattering process at a number of scattering angles both left and right of the zero-scattering-angle center line.

The neutron detectors were hydrogenous scintillators placed within a large collimator system at flight paths of $\sim$5 m. The relative energy-dependent efficiency of each detector was determined by observation of hydrogen-scattered neutrons at a fixed incident energy and varying scattering angles or by the observation of neutrons emitted during the spontaneous fission of ^{252}Cf, or by both methods.[9] The normalization of the relative detector sensitivities was determined at each incident energy relative to the well-known H(n;n) cross sections.[10] Uncertainties associated with the detector calibrations varied with measurement period but were generally 3 to 5 percent. They were the largest single contribution to the overall cross-section uncertainties. Further details of the detector calibration procedures are given in Refs. 9, 11, and 12.

The scattering samples were 2 cm long 2 cm diameter right cylinders placed at the focus of the ten time-of-flight collimators approximately 13 cm from the neutron source. Several carbon samples were fabricated from different stocks of pile graphite. The polyethylene (hydrogen) sample used for the above calibration procedures was dimensionally identical to the carbon samples.

Data acquisition was via an on-line digital computer using an 11 x 512 x 16 matrix consisting of 10 detectors plus a monitor, 512 time channels for each detector, and 16 energy-recoil bins per detector. Data reduction to cross section proceeded through an integrated data-processing system which included corrections for angular resolution, incident-neutron attenuation and multiple-event effects.[12] These correction procedures employed both analytical and Monte-Carlo computational techniques. Cross section uncertainties associated with the correction procedures were generally $\lesssim$2 percent. The statistical accuracy of the measured data was generally $\leq$2 percent except for the minima of a few distributions where the uncertainties increased to $\approx$5 percent.

III. EXPERIMENTAL RESULTS AND COMPARISONS WITH OTHER MEASURED AND EVALUATED DATA

A. Neutron Total Cross Sections

Initially, previously reported results were reviewed. These are of two general types: 1) those obtained using white-source techniques and 2) those obtained using monoenergetic methods. The two techniques have distinct advantages and drawbacks; thus the two types of results were examined separately. The input data consisted of all relevant neutron total cross sections available from the National Nuclear Data Center up to August 1977. Data reported otherwise in the literature was generally not available in the quantitative manner necessary for detailed review and thus were not used.

The input data sets were graphically inspected for general quality. Those sets that were judged seriously discrepant with the body of the information in cross-section magnitude, energy scale, or energy resolution were rejected. The overall data base and these judgements are outlined in Tables 1 and 2. The rejection criteria were generous as subsequent analysis was

TABLE 1. White-source Data Base

Authors	Comments
C. Uttley (36)	Used 0-2.8 MeV. Abandoned at higher energies due to poor resolution.
P. Yergin + (37)	Used 0.8-4.5 MeV .
P. Stoler + (16)	Used 0.8-4.5 MeV. Probably slight energy error at 3.0 MeV.
S. Cierjacks + (14)	Used 0.7-4.5 MeV. Best resolution.
R. Schrack + (13)	Used 0.01-0.57 MeV. Shows small ^{13}C resonance.
R. Schwartz + (15)	Used 0.5-4.5 MeV.
K. Diment (38)	Used 0-1.5 MeV.
D. Foster + (39)	Used 3.0 MeV-4.5 MeV. Abandoned at lower energies due to poor resolution.
F. Perey (17)	Used 0.3-4.5 MeV.
K. Nishinura + (40)	Used 0-250 keV.
L. Green + (41)	Abandoned due to apparently poor resolution, possibly due to an unusual technique.

TABLE 2. Monoenergetic-source Data Base

Authors	Comments
R. Block + (42)	Single value at ∿24 keV.
U. Fasoli + (20)	Used 0.5-4.5 MeV.
J. Cabe + (43)	Used 0.15-1.2 MeV.
S. Mubarakmand + (44)	Abandoned, few points not consistent with main body of data.
C. Ai + (45)	Abandoned, undue scatter of points.
R. Stooksberry (46)	Used 0.4-2.5 MeV.
G. Gorlov + (47)	Single value at 4.0 MeV.
P. Mooring + (48)	Used 0-600 keV.
A. Sorriax (49)	Abandoned, points appear systematically low.
G. Ambrosino + (50)	Used, only single value.
K. Seth et al. (51)	Abandoned, points appear systematically in. error.
J. Cabe + (52)	Abandoned because of undue fluctuations.
R. Wilenzick + (53)	Abandoned due to apparent systematic energy-dependent bias.
D. Fossan + (54)	Abandoned on second pass as apparently systematically low at ∿3.5 MeV.
C. Huddleston + (55)	Used 0.5-1.3 MeV.
H. Willard + (56)	Used 2.2-2.8 MeV.
J. Wills + (18)	Used to define 2.08 MeV resonance.
E. Bennett + (57)	Used values near 2.5 MeV.
R. Bondelid + (58)	Used values above 2.5 MeV.
R. Becker + (59)	Abandoned, very few points, appear high.
M. Walt + (60)	Used single value at 4.1 MeV.
W. Allen + (61)	Used, few values at low energies.

TABLE 2 (Contd.)

Authors	Comments
C. Storrs + (62)	Used values in range 2-3 MeV.
C. Hibdon + (63)	Used values below 0.2 MeV.
E. Hafner + (64)	Used values near 4 MeV.
N. Nereson + (65)	Abandoned due to coarse resolution.
H. Dvorack + (66)	Used values near 2.5 MeV.
R. Henkel + (67)	Used values near 3.5-4.5 MeV.
C. Bockelman + (19)	Used values from 1.2-3.2 MeV.
W. Good + (68)	Used, single value near 1 MeV.
G. Freier + (69)	Abandoned due to coarse resolution.
D. Miller (70)	Abandoned, the single value appears high.
H. Willard + (71)	Abandoned, values systematically high.
E. Bretscher + (27)	Abandoned, large fluctuations.
R. Fields + (73)	Used, few values below 1 MeV.
C. Bailey + (74)	Abandoned, very coarse resolution.
D. Frisch (75)	Used, few low energy values.
J. Whalen + (76)	Used, 0.1-1.5 MeV.
W. Zinn (77)	Abandoned, apparently anomalous value.

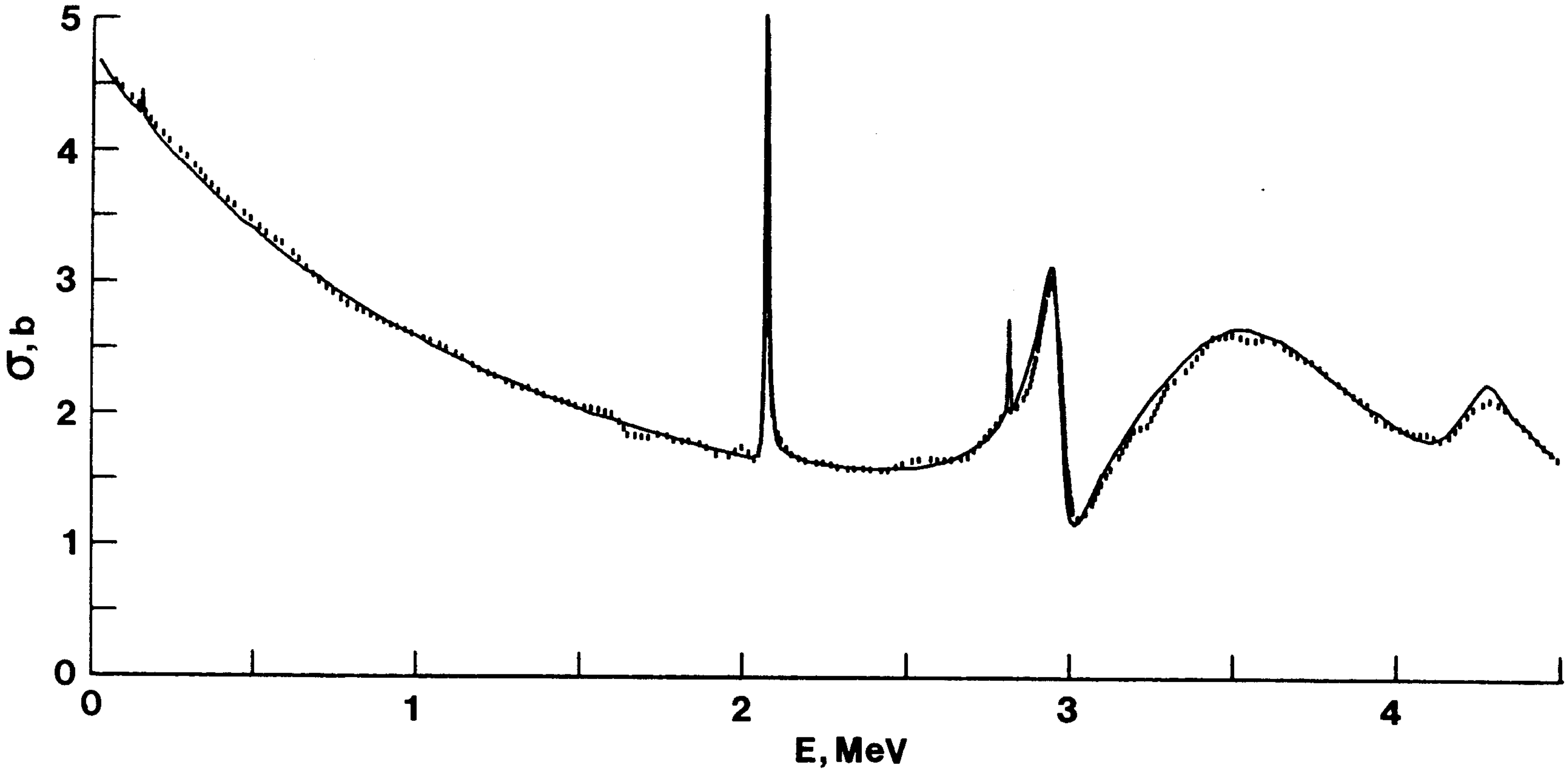
designed to further assess the validity of the data. Data sets with a large number of values in regions of slowly varying cross sections were averaged over 10 keV intervals, retaining the details of the original measurements in the regions of pronounced structure. Energy scales were not adjusted. Data uncertainties were accepted as stated by the authors. When no error statement was available a 3% uncertainty was assigned as a reasonable estimate of the accuracy of a typical transmission experiment. When data sets were averaged the RMS deviation from the mean was accepted as a measure of experimental error, limited to a minimum value of 1%. The two data groups and associated errors, corresponding to the two types of measurements, were assembled into two master data tapes and, as such, formed a data base corresponding to previously reported measurements. These tapes explicitly avoided any reference to data source.

The above two data groups were analyzed using 50 keV energy-averages in regions of slowly-varying cross sections. The averaging increment was a compromise between acceptable energy definition and a good average-sampling from a number of data sets. The weighted mean and average deviation from that mean was calculated in each averaging increment. Initially, all data within the increment were accepted. In ten successive steps data deviating from the mean by 20 to 2% were rejected and the mean re-evaluated. The result obtained with the most stringent 2% criteria was generally accepted as representative of a number of the most consistent values. In some instances too few values met the 2% criteria and the limit was relaxed to obtain a reasonable sample. This averaging-convergence procedure worked very well for the white source data where there were an abundance of measurements, but was less suitable for monoenergetic data where the measured values were more discrepant and less abundant.

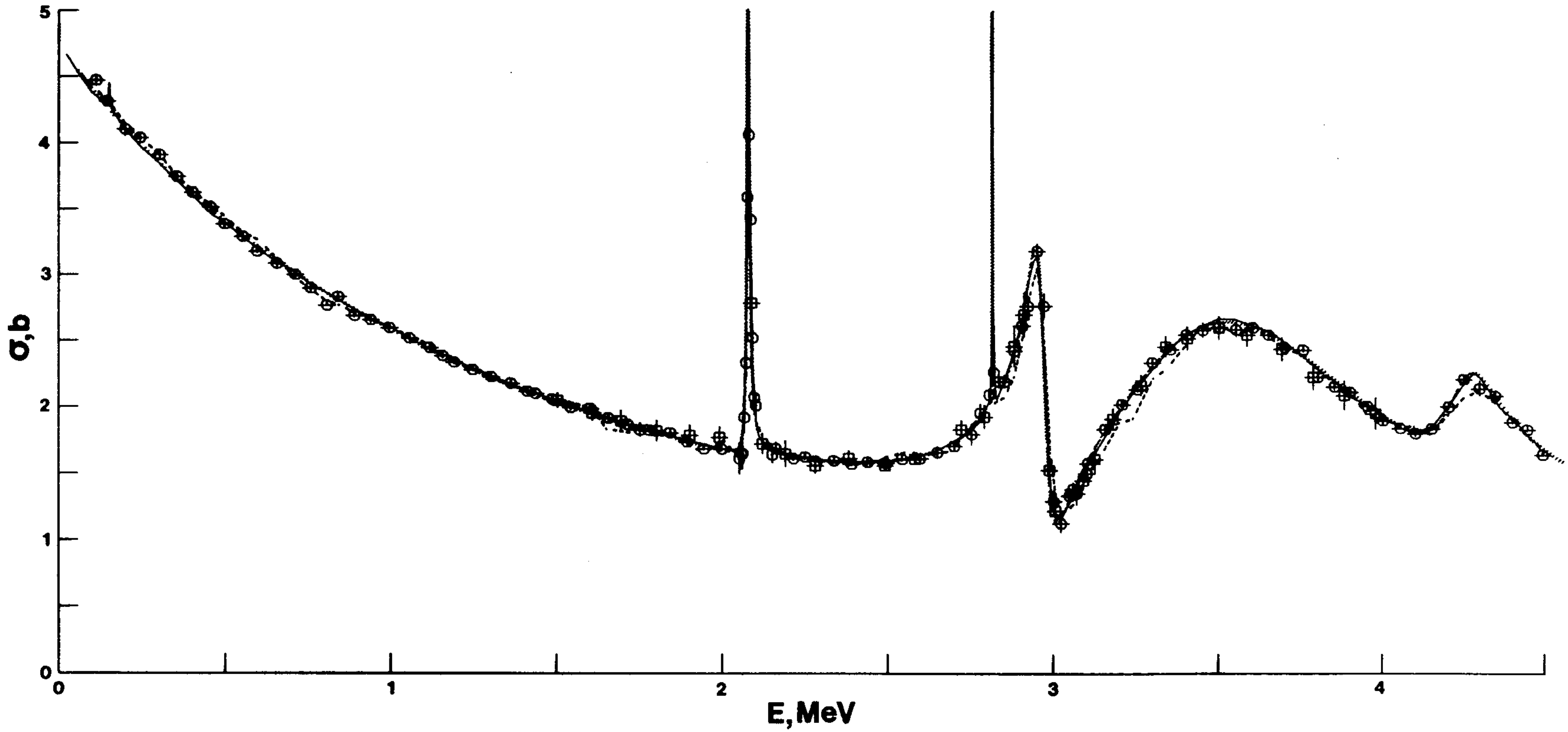
The above averaging procedures were not suitable in regions of prominent fluctuations near 150, 2080 and 3000 keV. These regions of structure were defined by subjectively selected data sets judged by quality of cross-section magnitude, energy scale, and energy resolution. When several sets of data appeared of equivalent quality an average was used. The small ^{13}C resonance at $\sim$150 keV was clearly evident only in the white-source data of Schrack et al.[13] It was included for completeness but has little relevance to the present interpretation. The white-source data of Cierjacks et al.[14] best define both the 2.08 and 2.81 MeV resonances and were used in the white-source estimates. These results are consistent with the lower resolution results of Schwartz et al.,[15] Stoler et al.[16] and Perey.[17] The energy scale of Cierjacks et al. for the 2.08 MeV resonance was shifted by $\sim$0.5 keV to agree with the "standard" energy of 2078 keV as given in a recent review by James.[7] The best monoenergetic definition of the 2.08 MeV resonance appeared to be in the work of Wills et al.[18] and that data was used in the monoenergetic summary. Again, there was an energy renormalization (of $\sim$1 keV) to agree with the standard value of James. No monoenergetic data appreciably resolves the 2.81 MeV resonance. The large resonance minimum near 3.0 MeV is best obtained from the white-source measurements of Perey,[17] Cierjacks et al.,[14] Stoler et al.[16] and Schwartz et al.[15] and from the monoenergetic measurements of Bockelman et al.[19] and Fasoli et al.[20] The white-source results of Refs. 14 and 17 were most consistent and an average was used in the present summary. The results of Ref. 16 appeared somewhat shifted in energy and those of Ref. 15 seemed to suffer from coarser resolution. The present monoenergetic summary uses an average of the results of Refs. 19 and 20 in the 3.0 MeV region. There were several other relevant monoenergetic results that were abandoned because of discrepancies in cross-section magnitude and/or energy scale.

The results of the above two summaries are compared in Fig. 1. They are reasonably consistent with some differences due to the limited monoenergetic data in some energy regions resulting in "scatter" (e.g. $\approx$1.7-1.9 MeV) of the values. There are some systematic differences of 1-2 percent below 1 MeV. Some differences about 2.8-3.0 MeV are probably due to lesser resolution in some of the monoenergetic measurements. The most serious differences are from 3.1 to 3.6 MeV where the monoenergetic results are systematically lower than those of the white-source measurements by 2-5 percent. Despite these discrepancies, the total cross section is relatively well-known with previously-reported white-source measurements giving the better resolutions and, probably, the better energy-average magnitudes. The proposed ENDF/B-V[a] evaluation is apparently a theoretical fit to the white-source data base in the energy region of interest here. Thus, as illustrated in Fig. 2, it is not surprising that the evaluation agrees with the present white-source summary to within $\lesssim$1 percent excepting only the $\approx$2.81 resonance which is only marginally defined in the best-resolution measurements.

The results of the present experiments were analyzed by forming weighted averages in 50 keV energy intervals in regions of slowly-varying cross section. In the resonance regions experimental results obtained with resolutions of <10 keV were selected. Results were obtained with sample thicknesses of 2-5 cm in the slowly-varying energy regions and with 2-3 cm thick samples in the resonance regions. The majority of the results were obtained with resolutions of 15-30 keV, i.e., values smaller than the above averaging increment. The energy scale was determined as outlined in Sec. II. The analysis accepted the statistical errors of the individual measurements and defined the uncertainties of the averaged values as weighted RMS deviations from the mean. Since the measured results were accumulated over a five-year period using many variations



1. Comparison of White-source (solid curve) and Monoenergetic (dashed curve) Summaries of Previously Reported Carbon Neutron Total Cross Section Results. (Here, and throughout these figures cross sections have been truncated to a maximum of five barns.)



2. Comparison of Neutron Total and Scattering Cross Sections of Carbon: a) circular data points = present measured total-cross-section values; b) square data points = angle-integral of present measured differential-elastic-scattering values; c) summary of previously reported white-source total-cross-section results = solid curve; d) summary of previously reported monoenergetic-source total-cross-section results = dashed curve; and e) preliminary ENDF/B-V total cross section = dotted curve and is essentially identical to the solid curve.

of the same basic apparatus, it was hoped that there was a good sampling of many systematic uncertainties that were not necessarily the same for each measurement period.

The present experimental results are compared with the above white-source and monoenergetic summaries and with the proposed ENDF/B-V evaluation in Fig. 2. The present results are in good agreement with the white-source summary and with the ENDF/B-V evaluation above several hundred keV. Except for only the narrow resonances and a very few measured values, the agreement is $\lesssim 1$ percent. The experimental uncertainties of the present work are generally of that order. Such agreement over such a wide energy range is probably not realized with any other single monoenergetic experimental data set. It was concluded that the present experimental results verify the above white-source summary and/or the proposed ENDF/B-V to approximately 1 percent and that either the white-source summary, the present results or a combination is suitable for the subsequent R-function interpretation of differential elastic scattering data. The only substantive differences are at the peak of the 2.08 MeV resonance, where the white-source results provide better resolution and probably more accurate energy scales, at the maximum of the broad resonance at ≈ 3.6 MeV, where there may be a real and unresolved difference of 1-2 percent and below a few hundred keV where the present results tend to be 1-2% higher than the evaluation. These small differences are further discussed in Sec. IV, below.

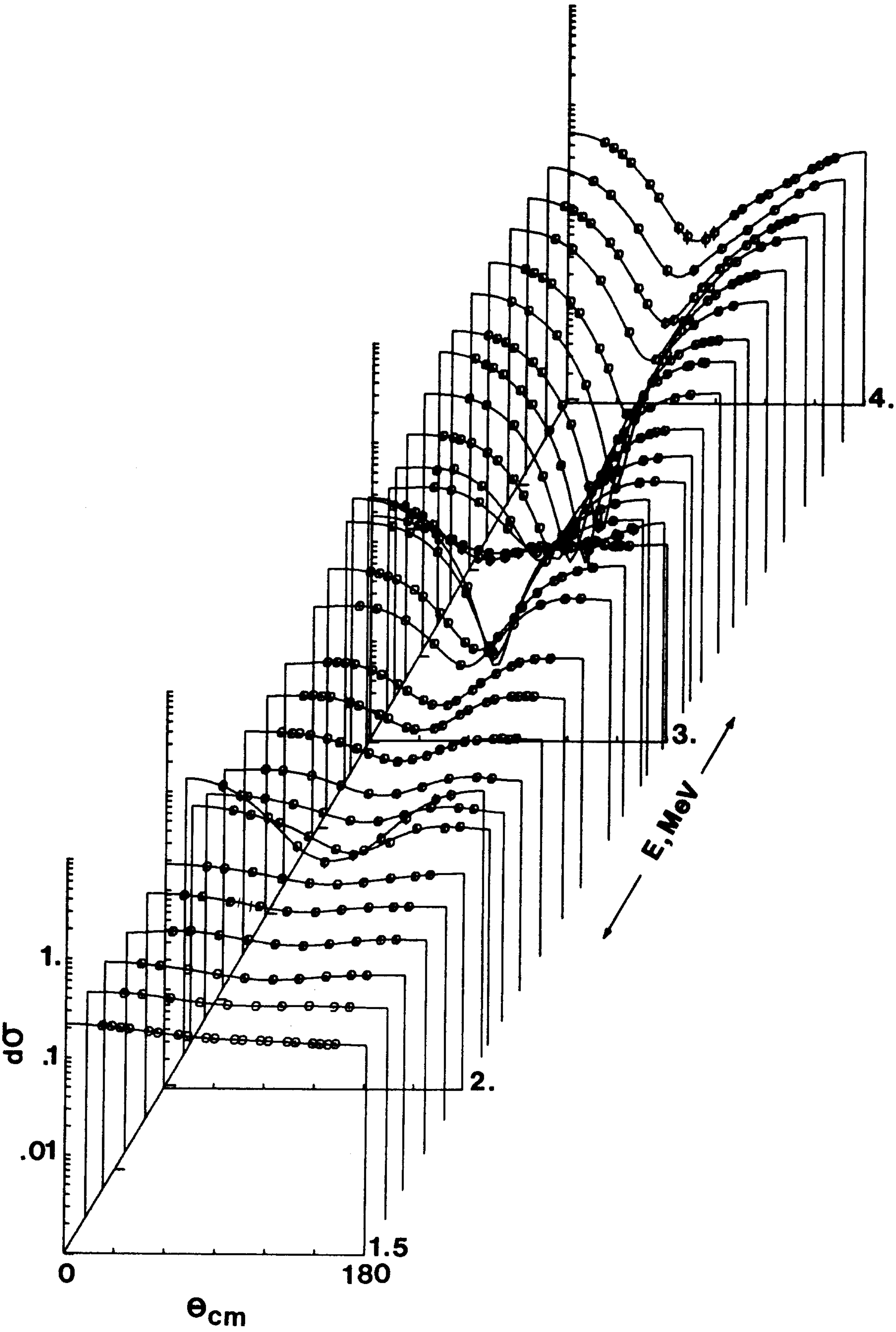
B. Neutron-elastic-scattering Cross Sections

The present results were constructed by averaging the values obtained in measurements made over an extended period. The incident energy resolutions were in the range 20 to 50 keV. The various measured distributions were not always obtained with identical resolutions and/or incident energies. When the incident energies were equivalent to within the resolution functions the results were averaged. In some instances more than ten experimental distributions encompassing in excess of 100 individual differential cross sections were involved in the construction of a single average distribution. These procedures led to very small statistical uncertainties and reduced systematic errors. Many of the systematic errors were peculiar to the particular measurement, e.g. detector calibration, and essentially randomly distributed as outlined above. Other systematic errors were common to all measurements, e.g. multiple-event corrections, and thus not reduced by the averaging procedures. The estimated uncertainties associated with the latter type of systematic error were 1 to 2 percent and thus defined the minimum uncertainties in the averaged results.

The present results were least-square fitted with a Legendre-polynomial expansion of the form

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}[1 + \sum_{i=1}^{6} w_i P_i] \qquad (1)$$

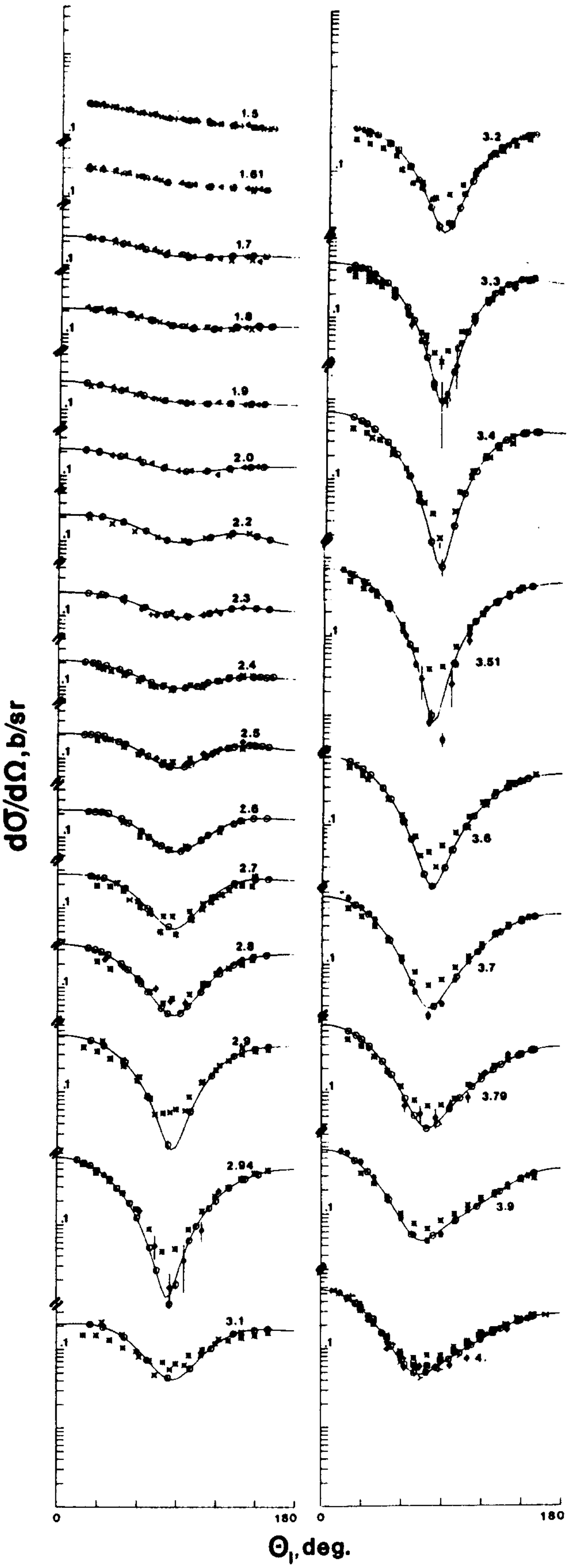
with all values expressed in the center-of-mass coordinate system. The results of these fitting procedures are compared with the measured differential cross section values in Fig. 3. The consistency between the measured values and the fit of Eq. 1 was generally better than the experimental uncertainties. The fitting procedure also provided the angle-integrated cross sections. These are compared with the measured total cross sections in Fig. 2. Generally, the agreement between measured total and angle-integrated scattering cross sections was in the range 1 to 3 percent. Very near sharp resonance structure the differences are larger as expected from the different experimental resolutions employed in the two types of measurements. Excepting these limited regions, in no instance do the measured total and angle-integrated scattering cross sections differ by more than $\sim$5 percent. These 3



3. Summary of Present Measured Differential-elastic-scattering Cross Sections. Measured values are indicated by data points. Curves denote the results of a least-square fit of Eq. 1 to the measured values. Dimensions are cross section in b/sr, angle in degrees (center-of-mass system) and energy in MeV.

differences are less than often encountered between various previously reported total cross section measurements and of the same order of magnitude as the difference between white-source and monoenergetic-source total cross sections reported in the literature as outlined above.

The present differential elastic scattering values were extensively compared with those reported in the literature. The results given in the literature were assembled from the files of the National Nuclear Data Center as available August 1977 and defined in Refs. 21 to 35. A qualitative inspection indicated that some of the values obtained from the literature were of very poor quality and these were immediately rejected. The remaining data sets were compared with the present results distribution by distribution. In doing so it was not always possible to obtain an exact correspondence in either incident energy and/or energy resolution and thus the literature values nearest the energy and resolutions of the present work were used. These variations in energy resolution and/or scale introduced some differences between measured values particularly in the limited regions of sharply fluctuating structure. A number of these comparisons are illustrated in Fig. 4. Below approximately 2.0 MeV the present results are in very good agreement with those of Lane et al.[24] and Ahmed et al.[21] From approximately 2.1 to 2.9 MeV the present results are in reasonable agreement with those of Wills et al.[27] and Rodgers et al.,[28] excepting the small region of structure near 2.8 MeV. In some instances there is good agreement with the results of Fasoli et al.[20] and of Meier et al.[29] and in other instances considerable disagreement. The present values are not consistent with those of Demanis et al.[26] From 3.1 to 3.9 MeV the present distributions display very low minimums near 90 deg. Throughout this region the present values are in remarkably good agreement with those of Galati et al.[32] The results of



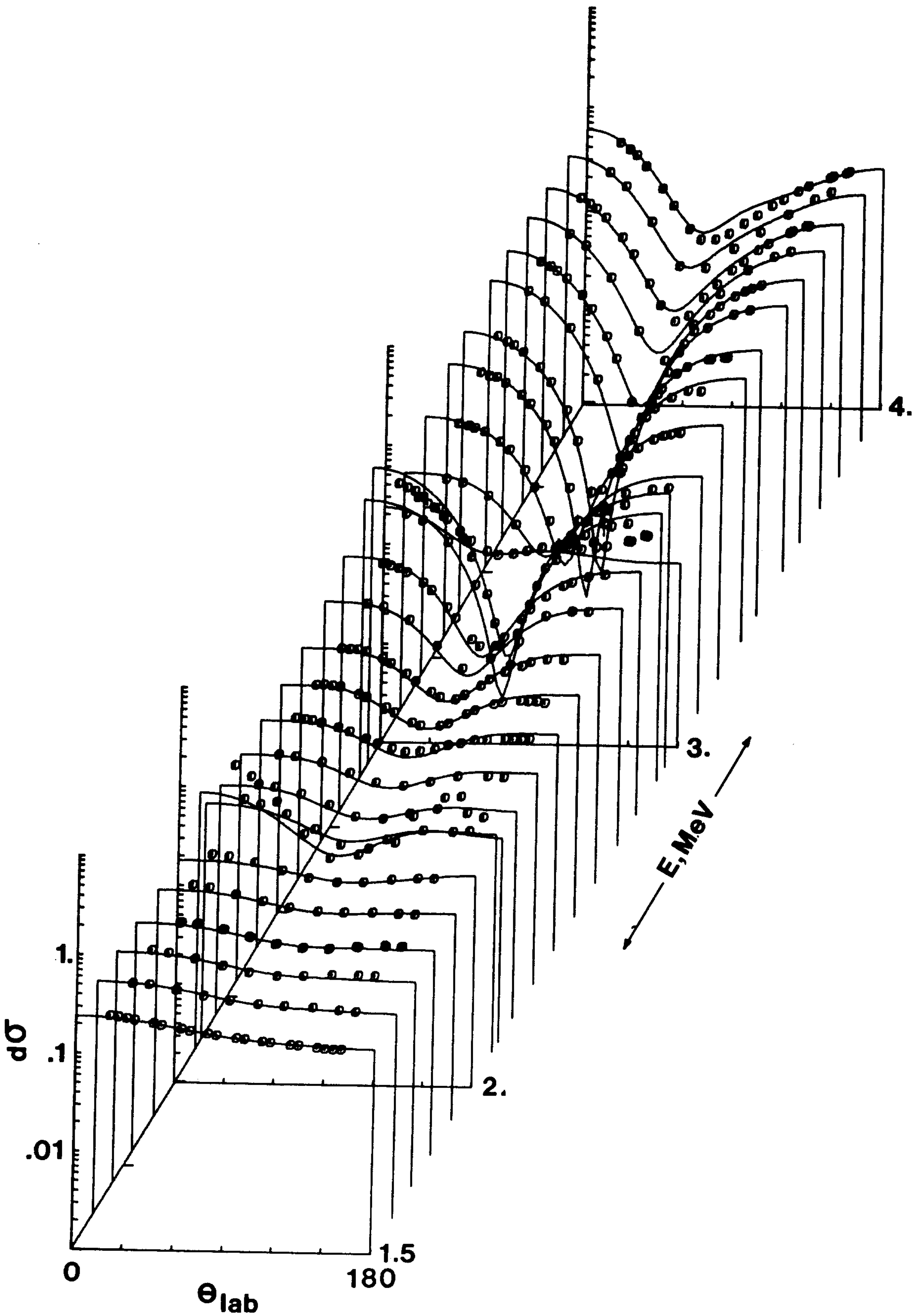
4. Comparison of Present Differential-elastic-scattering Results (circular data points and curves) with values taken from the literature (other symbols) as outlined in Sec. III of the text.

Fasoli et al.[20] and Meier et al.[29] generally do not reproduce the minimums observed in the present work or that of Ref. 32. Shortcomings in the area of deep minima can be due to improper treatment of multiple-event corrections. Near 4.0 MeV the present results are in reasonable agreement with those of Gorlov et al.,[33] Walt and Beyster,[35] Boschung et al.[34] and Galati et al.[32] Again, the results of Ref.[20] do not reproduce the minimum values observed in the present work. Generally, any comparisons near approximately 2.0 or 3.0 MeV are not particularly meaningful due to the very-sharp-resonance effects in these areas.

Angular distributions were constructed from the proposed ENDF/B-V file, averaged to resolutions approximately equivalent to those of the present experiments. These averaged evaluated results are compared with the present measured values in Fig. 5. The agreement between the present measurements and the evaluation at the lower energies is good. At higher energies the agreement is not as satisfactory and near 4.0 MeV the differences can be 20 to 30 percent at some angles. Thus the present measurements suggest that the evaluation is a suitable reference-standard file below 2.0 MeV. At higher energies there remains question at some energies and angles.

IV. R-FUNCTION INTERPRETATION

The present interpretation is confined to the present experimental values excepting only the addition of a precision thermal total cross section value.[78] It was assumed that the neutron interaction was entirely due to elastic scattering. Neutron capture is small in the energy range of interest (the order of micro-barns) and no other reaction channels are significant factors below 4.0 MeV. It was further assumed that elemental carbon consisted entirely of the isotope ^{12}C ($\sim$99% natural abundance). A known and large ^{13}C ($\sim$1% abundance) resonance at $\sim$150 keV was ignored. Moreover,



5. Comparison of Present Differential-elastic-scattering Results (data points) with Corresponding Results Taken from ENDF/B-V (curves). Dimensions are cross section in b/sr, angle in degrees (laboratory system) and energy in MeV.

ancillary measurements of elastic scattering from ^{13}C indicated that perturbations due to this isotope would not distort the present elemental results appreciably beyond the experimental uncertainty excepting at a few selected energies. Even then perturbations may be small due to the fortuitous similarity of the angular distributions of neutrons elastically scattered from elemental carbon and ^{13}C.

With the above assumptions the R-matrix reduces to an R-function of the form

$$R_{\ell J} = \sum_{\lambda=1}^{n} \frac{\gamma^2_{\lambda\ell J}}{E_{\lambda\ell J} - E} + R^{\infty}_{\ell J} \tag{2}$$

where $\gamma^2_{\lambda\ell J}$ and $E_{\lambda\ell J}$ are the reduced width and level energy of the λ resonance with orbital angular momentum ℓ and spin J.[79] Contributions from distant resonances outside the energy region of immediate interest are represented by the term $R^{\infty}_{\ell J}$. Following the method of Holt et al.,[1] the $R^{\infty}_{\ell J}$ was expanded in terms of the neutron energy:

$$R^{\infty}_{\ell J} = \sum_{\mu} \sum_{n=0} (\gamma^2_{\mu\ell J}/E_{\mu\ell J})(E/E_{\mu\ell J})^n \tag{3}$$

for $E_{\mu\ell J} > E$ and where μ represents those resonances not explicitly considered. If we assume $E_{\mu\ell J} >> E$, then

$$R^{\infty}_{\ell J} \simeq R_{0\ell J} + R_{1\ell J} \cdot E \tag{4}$$

where $R_{0\ell J}$ and $R_{1\ell J}$ are energy independent. This approximation is valid if there are no resonances of significant width near the energy region of interest. Clearly, in that case $R^{\infty}_{\ell J}$ would have a rapid variation in energy. Fortunately, for the $^{12}C + n$ system Eq. 4 was found to be a good approximation below 4.0 MeV provided that the 4.3 MeV p-1/2 level was explicitly included in the analysis. When a quadratic term in energy was added to Eq. 4 there was no significant improvement in the quality of the fit to the measured data. Equations 2 and 4 may be used to compute the neutron-scattering phase shifts $\delta_{\ell J}$,

$$\delta_{\ell J} = -\phi_\ell + \tan^{-1}\left\{P_\ell R_{\ell J}/[1 - (S_\ell - B_{\ell J})R_{\ell J}]\right\} \tag{5}$$

where ϕ_ℓ, P_ℓ and S_ℓ are the hard-sphere phase shift, penetration factor and shift-factor, respectively. The $B_{\ell J}$ terms represent the boundary-condition constants. The neutron total cross section can be readily calculated from the phase shifts by

$$\sigma_T = \frac{4\pi}{k^2}\sum_{\ell=0}^{3}\left[\ell \sin^2\delta_{\ell,\ell-\frac{1}{2}} + (\ell + 1)\sin^2\delta_{\ell,\ell+\frac{1}{2}}\right] \tag{6}$$

where k is the neutron wave number, $k = 0.21968\ A/(A + 1)\sqrt{E_n}(\mathrm{MeV})\gamma\ \mathrm{fm}^{-1}$, and ℓ is the orbital angular momentum. In order to compute the differential cross section, $(d\sigma/d\Omega)$, and the polarization, p, we introduce the spin-flip amplitude, h, and the non-flip amplitude, g, so that:

$$\frac{d\sigma}{d\Omega} = |g|^2 + |h|^2 \tag{7}$$

and

$$p = \frac{2\mathrm{Re}(gh^*)}{|g|^2 + |h|^2} \tag{8}$$

As a check of the least-square fitting procedures two independent computational codes were used. One was an adaptation of the COMBO program of Lane et al.[80] and the other the Yale University program of R. Holt.[81] The programs were independent chi-square fitting procedures which gave consistent results. The parameters γ_λ^2, E_λ, $R_{0\ell J}$ and $R_{1\ell J}$ were adjusted to obtain the optimum fit to the data. The boundary conditions and radius were fixed at the values of Holt et al.[1,81] The radius was sufficiently large (4.61 F) to assure a reasonable consistency with the physical concepts underlying the theory. All negative-resonance energies were set equal to the values given in Ref. 82 and their respective reduced widths were determined by fitting the present data.

The energies and widths of the narrow resonances at 2.078 MeV (d-5/2) and 2.810 MeV (f-5/2) were not defined by the present measurements. Therefore, the energies were set equal to the values reported in the literature[7] and the widths adjusted to correspond with previously reported total cross section results (see above discussion). The angular momentum (ℓ) and (J) values were taken from Ref. 82. All resonances at energies above the measured energy range (i.e. >4.5 MeV) were incorporated into the R^{∞} terms except for the addition of a narrow p-3/2 resonance at 4.95 MeV. Its parameters were fixed to values reasonably consistent with previous total cross section results (e.g. Ref. 14).

The experimental results in the energy regions of 2.08 and 3.0 MeV were very sensitive to the exact energy scale and energy resolutions and thus were omitted from the present analysis. The analysis was terminated at the upper energy limit of the present differential-elastic-scattering measurements (i.e. $\gtrsim$4.0 MeV). Only total neutron cross sections were available from 4.0 to 4.5 MeV and with reduced accuracy. Moreover, the upper-energy extreme of the range was influenced by contributions from resonances well beyond the measured energy interval. Thus the total cross section behavior from 4.0 to 4.5 MeV was determined by parameter adjustment rather than fitting.

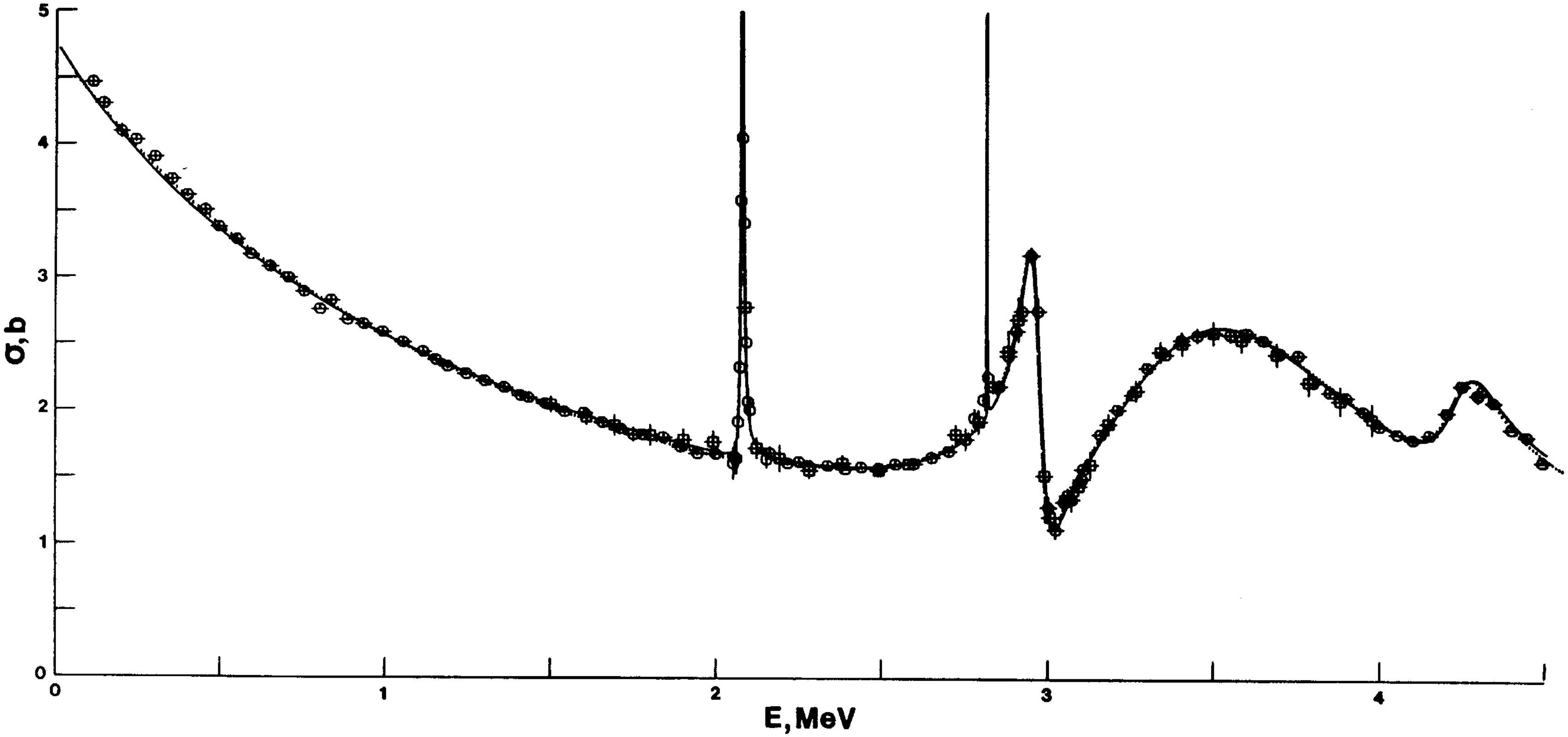
The parameters of Holt et al.[1] were used as a starting point. Initial fitting was based only on the total cross section. After reasonable convergence was obtained using the total cross section data the differential-elastic scattering cross sections were introduced and the analysis repeated using the combined neutron total and differential-elastic-scattering cross section data sets. After convergence using the combined data set small adjustments were made to improve agreement at either extreme of the data set (i.e. at thermal and above 4.0 MeV). The entire procedure was repeated several times finally resulting in the parameter set given in Table 3.

The neutron total cross sections calculated with the parameters of Table 3 are compared with the present measured total and angle-integrated elastic-scattering cross sections and with the preliminary ENDF/B-V total cross sections in Fig. 6. Generally the present calculated and measured total cross sections are in agreement to well within the experimental uncertainties. However, there are deviations at either extreme of the measured energy range. Below several hundred keV the present measured values are inconsistent with the well established thermal total cross section.[78] The latter was a forced constraint on the fitting procedure. As a consequence the values calculated from the parameters are 1 to 1½% lower than the measured values to $\stackrel{\sim}{\sim}$300 keV. The low-energy shape of the total cross section is governed by the s-wave resonance at -1.857 MeV. Contributions from other bound p- and d-wave resonances were found to influence angular distributions at higher energies ($\lesssim$500 keV). The fit indicated that these bound levels should have small widths. In fact, the width of the p-3/2 bound level was found to be an order of magnitude smaller than that given in Ref. 1. With these resonance configurations the calculated relative low-energy total cross sections differ from the present measurements by $\stackrel{\sim}{\sim}$1% irrespective of the thermal cross section value. These considerations suggest that the present experimental total cross section values are systematically too large by 1 to 1½% below several hundred keV. This is a small discrepancy, reasonably attributed to systematic energy scale and resolution errors in the difficult region near the threshold of the $^{7}Li(p,n)^{7}Be$ source reaction. However, it is noted that a large ^{13}C resonance has been reported at $\stackrel{\sim}{\sim}$150 keV.[85] It would be averaged in the present broad-resolution measurements with the net

TABLE 3. R-function Parameters[a]

Channel/Parameter		ℓ-J Values					
		0, 1/2	1, 1/2	1, 3/2	2, 3/2	2, 5/2	3, 5/2
λ_1	γ^2	0.666	-	0.050	0.165	-	0.006[b]
	E_R	-1.887[c]	-	-1.267[c]	2.930	-	2.810[b]
λ_2	γ^2	-	0.080	0.010[b]	0.968	0.017[b]	-
	E_R	-	4.200	4.940[b]	3.510	2.078[b]	-
$R_{0\ell J}$		0.0245	0.09	0.261	0.250	0.065	0.0
$R_{1\ell J}$		-	0.050	0.050	0.000	0.0	0.0
Boundary, $B_{\ell J}$		0.0	-0.2	-0.18	-1.0	-1.30	-1.3

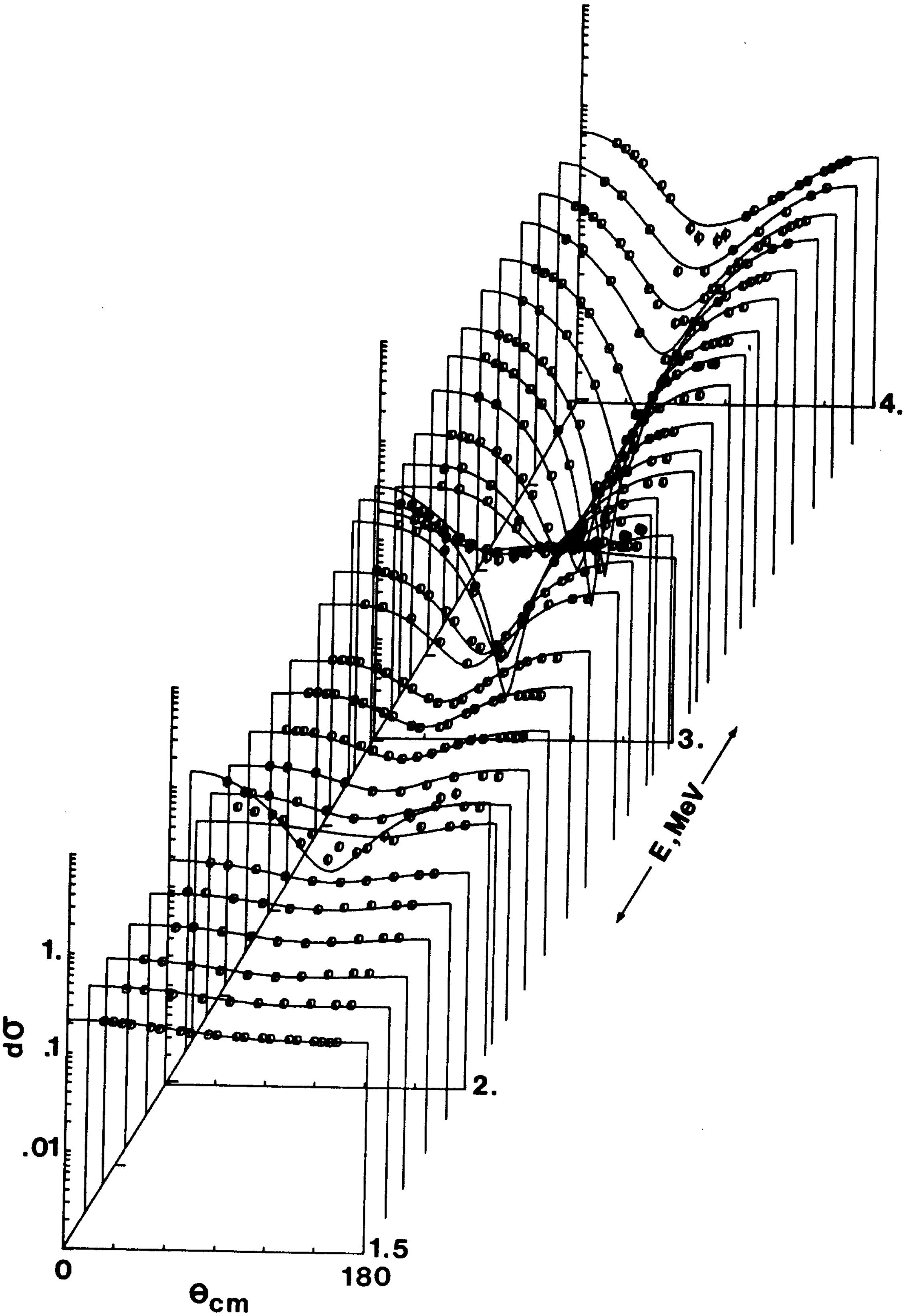
[a] All energies in MeV, all lengths in fermis, radius = 4.61 F.
[b] Estimated from values given in literature, not adjusted by fitting to present data set.
[c] Negative energy values taken from Ref. 85, not adjusted by fitting to present data set.



6. Comparison of: a) total neutron cross section calculated from the present R-function parameters (solid curve), b) present measured total cross sections (circular data points), c) angle-integral of present measured differential-scattering cross sections (square data points), and d) the total cross section as given by ENDF/B-V (dotted curve, essentially identical to the solid curve).

effect of increasing the present measured values from those calculated from the ^{12}C parameters by $\sim$1% at $\sim$150 keV. Thus the difference between measured and calculated neutron total cross sections at low energies is in the direction and of the magnitude expected from the ^{13}C contaminant. Moreover, there is always the possibility of additional and unknown resonance contributions at these low (and other) energies. At the extreme upper energy limit of the measurements (i.e. >4.0 MeV) the comparison of measured and calculated neutron total cross sections is less satisfactory. This is not surprising as the total cross section measurements in this region are not of as good a quality as at lower energies and the experimental energy resolution probably compromises the definition of the 4.21 MeV resonance. Moreover, the fitting procedures are strongly influenced by resonances at energies well above the measured range whose contributions are only approximated by the R^{∞} term. Over the large majority of the measured energy range (i.e. $\sim$0.3 to 4.0 MeV) the calculated neutron total cross sections agree with the present measured values to within $\lesssim$1%. Throughout the energy range thermal to >4.0 MeV the neutron total cross section calculated from the present parameter set agrees with the total cross section given by the preliminary ENDF/B-V (which assumes the element is entirely ^{12}C) to within $\lesssim$1%. That agreement suggests that the neutron total cross section of elemental carbon is known to $\sim$1% to >4.0 MeV and thus can serve as a useful secondary standard cross section.

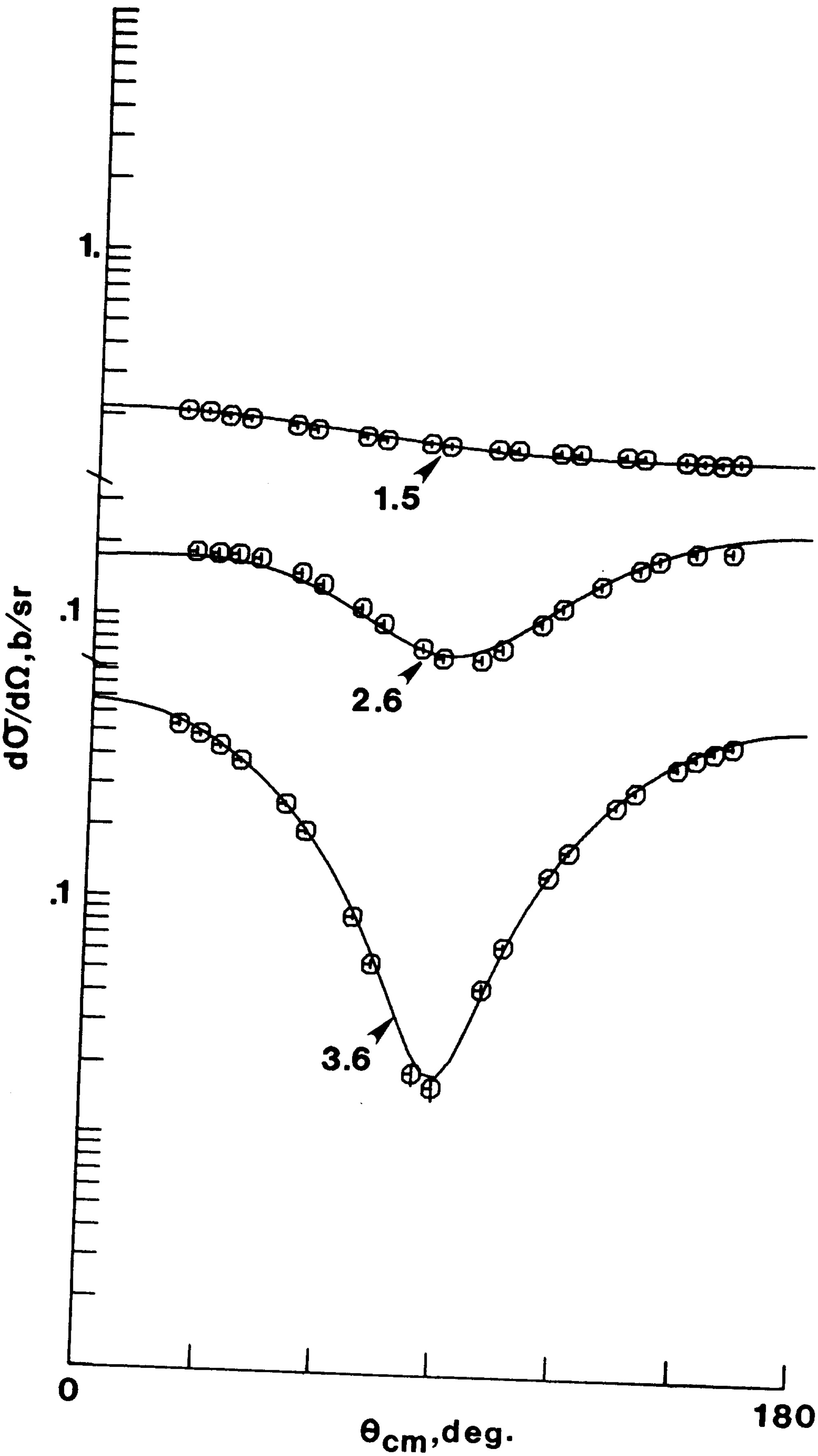
Measured and calculated neutron differential-elastic-scattering cross sections are generally compared in Fig. 7 and some more detailed specific examples are given in Fig. 8. Away from the fluctuating resonance regions about 2.078 and 3.0 MeV the agreement between measurement and calculation is generally very good. Comparisons near 2.078 and 3.0 MeV are not reliable as



7. Comparison of Measured Differential-elastic-scattering Cross Sections (data points) with Those Calculated from the Present R-function Parameters (curves). Dimensionality is the same as for Fig. 3.

very small uncertainties in either the incident energy scale or energy resolution of the measurements can result in large cross section changes. There is a tendency for the calculated back-angle cross sections near 1.7 and 2.4 MeV to lie higher than the measured values by one-to-two-standard deviations. This systematic trend may, in part, be due to contributions from ^{13}C as several narrow ^{13}C resonances are known to exist in these energy regions.[83] There is also a discrepancy near 4.0 MeV where the calculated differential values do not show as deep a minimum near 90° as do the measured values. This discrepancy may be attributed to resonances at energies well above the measured range and not fully accounted for by the R^{∞} terms. In addition, ^{13}C is known to have a large resonance in the total cross section near 4.0 MeV.[83] Below the energy range of the present differential measurements (i.e. below 1.5 MeV) the present calculations are descriptive of the measured differential-elastic-scattering cross sections reported by Lane et al.[84] The present calculated differential elastic scattering cross sections are similar to those of the preliminary ENDF/B-V over broad-energy ranges as indicated by the data comparison of Figs. 5 and 7 (the data points are identical in both figures). The agreement is to within several percent below 2.0 MeV and to within $\sim$5% at higher energies. Exceptions are limited regions about 2.078 and 3.0 MeV, very deep interference minima near 3.4 MeV and the 4.0 MeV region. The latter is a particularly difficult region not well represented by either the present calculations or the ENDF/B-V evaluation. These comparisons suggest that carbon is a good secondary scattering standard below $\sim$2.0 MeV and similarly useful to 4.0 MeV if care is taken to avoid the above noted areas of uncertainty.

The scattered-neutron polarizations can be a sensitive indicator of the validity of R-function parameters. Polarizations calculated with the present



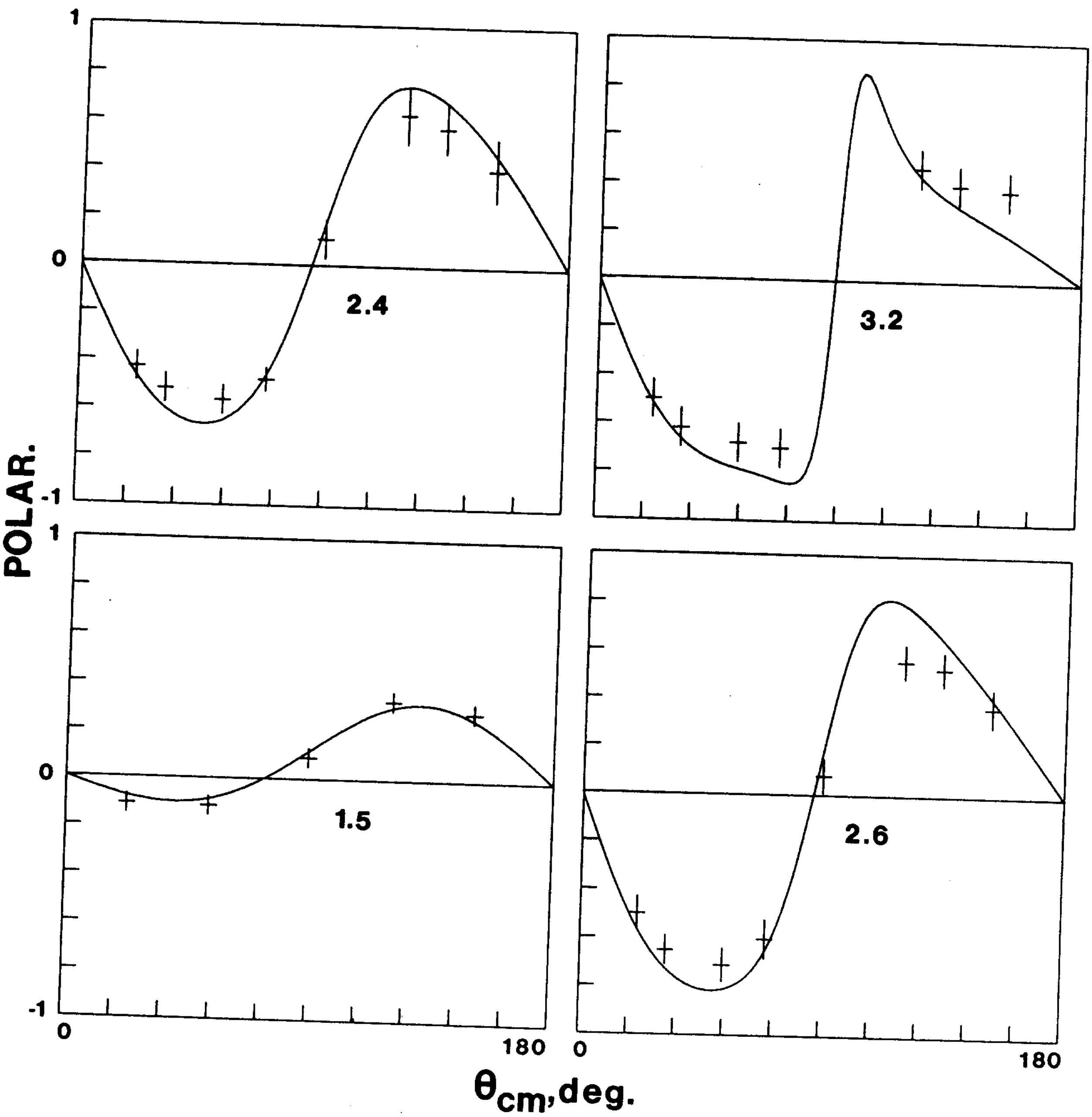
8. Comparison of Measured (data points) and Calculated (from the present R-function parameters, curves) Elastic-scattering Distributions at Incident Energies of 1.5, 2.6, and 3.6 MeV. Vertical bars indicate estimated experimental uncertainties.

parameters are compared with the measured results of Holt[81] and of Lane et al.[80,84] in Fig. 9. Although the polarizations were not an input to the present fitting procedures the calculated polarizations are descriptive of measured results reported elsewhere. This is not particularly surprising as the present parameter set (Table 3) is similar to that proposed by Holt from an analysis of observed polarizations.[81]

V. SUMMARY COMMENTS

The present monoenergetic-source results provide a detailed knowledge of the neutron total cross sections of elemental carbon from 0.1 to 4.5 MeV to accuracies of $\stackrel{\sim}{\sim}$1%. These results are in reasonable agreement with averages constructed from previously reported white- and monoenergetic-source experimental results. The present differential elastic scattering measurements define the respective broad resolution cross sections to few-percent accuracies from 1.5 to 4.0 MeV. The angle-integral of the differential elastic scattering cross sections is consistent with the measured neutron total cross sections to within a few percent considering the variations in the respective energy scales and resolutions. The present differential elastic scattering values agree with some previously reported results and are markedly different from others. In some instances the discrepancies appear attributable to poor or non-existent multiple-event corrections in the previous work.

The present experimental results provide a comprehensive basis for the interpretation of the neutron+^{12}C interaction in the few MeV range. Such an interpretation was carried out in the framework of the R-matrix assuming that the interaction with the elemental target was entirely due to the prominent isotope, ^{12}C, and that the excited structure of ^{13}C is well established over



9. Comparisons of Calculated (from present R-function parameters, curves) Scattered-neutron Polarizations and Measured Values Reported by Lane et al.[82] (1.5 MeV) and by Holt.[83]

the relevant energy range. Parameters were derived by detailed fitting of the R-function to the present total and differential-scattering cross section results. Neutron total cross sections calculated with the resulting R-function parameters generally agreed with the measured values to within $\sim$1%. An exception was the region 0.1-0.25 MeV where the broad resolution elemental total cross section is appreciably perturbed by ^{13}C contributions not considered in the present interpretation. The differential-elastic-scattering cross sections calculated from the R-function parameters generally agreed with the measured values to within $\sim$5% and frequently the agreement was far better. However, there were regions of systematic and larger deviations (notably near 1.7, 2.4, and 4.0 MeV) where the ^{13}C of the elemental target is known to display large resonances. With the above qualifications, the R-function parameters deduced from the present experiments provide a suitable mechanism for the interpolation of the measured neutron total and scattering cross sections of carbon in both energy and angle. Moreover, these parameters well describe differential-elastic scattering at energies much lower than those of the present experiments (e.g. at $\sim$0.5 MeV) and the calculated scattered-neutron polarizations are as consistent with measured values reported elsewhere as those obtained using models specifically developed in the context of polarization.

The present measured and calculated neutron total and differential-elastic-scattering cross sections are in reasonable agreement with those given in the preliminary ENDF/B-V evaluation. Discrepancies between the present total cross sections and those of the evaluation are generally $\lesssim$1% except for regions where ^{13}C is a potential contribution not dealt with in either the present interpretation or, apparently, the ENDF/B-V evaluation. Below $\sim$2.0 MeV the present differential-elastic-scattering cross sections generally agree with those of ENDF/B-V to within a few percent. There is similar agreement at higher energies providing care is taken to avoid results in regions unduly sensitive to small variations in energy scale and/or resolution or where ^{13}C contributions are a potential hazard. The differences between the present angle-integrated cross sections and those of ENDF/B-V, while very small, are beyond the tolerance set forth in the relevant ENDF/B-V uncertainty files.[86]

The present results and the above remarks suggest that the neutron total and scattering cross sections of elemental carbon are a good secondary standard if employed with care so as to avoid uncertainties due to resonance fluctuations and ^{13}C perturbations. This standard can be particularly useful in routine verifications of the performance of instruments used in other measurements. In addition, certain resonances are recognized as energy-calibration points as defined by James.[7] Appreciable improvement in the neutron total and scattering cross sections of elemental carbon in the few MeV range will require considerably more effort, particularly in the attention to detailed factors such as ^{13}C perturbations.

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*Throughout, the ENDF/B-V file refers to the preliminary carbon evaluated data file submitted to CSEWG by C. Fu and F. Perey (1978).

REFERENCES

1. R. Holt, A. Smith and J. Whalen, Natl. Bureau of Stds. Pub., NBS-425 (1975).

2. S. Cox and P. Hanley, Bull. Am. Phys. Soc., 60 121 (1971).

3. J. Gibbons and H. Newson, Fast Neutron Physics, Vol. 1, Eds. J. Marion and J. Fowler, Interscience Pub., NY (1960).

4. R. Schwartz et al., Natl. Bur. Stds. Pub., NBS-138 (1974).

5. S. Cierjacks et al., Karlsruhe Report, KFK-1000 (1968).

6. J. Meadows, Argonne Natl. Lab. Report, ANL/NDM-25 (1977).

7. G. D. James, Proc. Sym. on Neut. Stds., Natl. Bur. of Stds., Pub. NBS-SP 493 (1977).

8. A. Smith et al., Nucl. Instr. and Methods, 50 277 (1967); see also P. Guenther et al., Phys. Rev., C12 1797 (1975).

9. P. Guenther et al., Nucl. Instr. and Methods, 140 397 (1977).

10. J. Hopkins and G. Breit, Nucl. Data, A9 137 (1971).

11. P. Guenther et al., Phys. Rev., C12 1797 (1975).

12. P. Guenther, Univ. of Ill. Thesis, to be published.

13. R. Schrack et al., Bull. Am. Phys. Soc., 19 573 (1974).

14. S. Cierjacks et al., Karlsruhe Report, KFK-1000 (1968).

15. R. Schwartz et al., Bull. Am. Phys. Soc., 15 567 (1970).

16. P. Stoler et al., Bull. Am. Phys. Soc., 15 1668 (1970).

17. F. Perey, Oak Ridge Natl. Lab. Report, ORNL-4823 (1972).

18. G. D. James, See Ref. 7.

19. J. Wills et al., Phys. Rev., 109 891 (1958).

20. C. Bockelman et al., Phys. Rev., 84 69 (1951).

21. U. Fasoli et al., Nucl. Phys., 205A 305 (1973).

22. N. Ahmed et al., Proc. 2nd Inter. Conf. on Nucl. Data for Reactors, Helsinki, IAEA Press (1970).

23. H. Willard et al., Phys. Rev., 98 669 (1955).

24. R. Lane et al., Ann. Phys., 12 135 (1961).

25. R. Lane et al., Phys. Rev., 188 1618 (1969).

26. C. Muehlhause et al., Phys. Rev., 103 720 (1956).

27. F. Demanis et al., Lett. Nuovo Cimento, 8 259 (1973).

28. J. Wills et al., Phys. Rev., 109 891 (1958).

29. U. Fasoli et al., See Ref. 21.

30. W. Rodgers et al., Chicago Oper. Report, COO-1573-33 (1967).

31. R. Meier et al., Helv. Phys. Acta., 27 577 (1954).

32. H. Knox et al., Nucl. Phys., A217 611 (1973).

33. M. Hosoe Masanao and S. Suzuki, Phys. Soc. of Japan J. 14 699 (1959).

34. W. Galati et al., Phys. Rev., C5 1508 (1972).

35. G. Gorlov et al., J. Dok., 158 574 (1969).

36. P. Boschung et al., Nucl. Phys., A161 593 (1971).

37. M. Walt and J. Beyster, Phys. Rev., 98 677 (1955).

38. C. Uttley, Data obtained from the National Nuclear Data Center (NNDC).

39. P. Yergin et al., Proc. Conf. on Nuclear Cross Sections and Technology, Vol. 1, 690 (1966).

40. K. Diment, EANDC Report, EANDC-UK-94 (1968).

41. D. Foster and D. Glasgow, Phys. Rev., C3 576 (1971).

42. K. Nishinura et al., data obtained from the NNDC.

43. L. Green et al., Proc. Conf. on Nuclear Cross Sections and Technology, Vol. 1, 325 (1971).

44. R. Block et al., Nucl. Sci. and Tech. (Japan), 12 1 (1975).

45. J. Cabe et al., CEA Report, CEA-R-4524 (1973).

46. S. Mubarakmand et al., Nucl. Inst. and Methods, 115 345 (1974).

47. C. Ai et al., Nucl. Sci. (Taiwan), 11 179 (1974).

48. R. Stooksberry, Nucl. Sci. and Eng., 51 235 (1973).

49. G. Gorlov et al., Yadernaya Fizika, 6 663 (1968).

50. P. Mooring et al., Nucl. Phys., 82 16 (1966).

51. A. Sorriax, Comptes Rendus, 260 3045 (1965).

52. G. Ambrosino et al., CEA Report, CEA-2399 (1964).

53. K. Seth et al., Nucl. Phys., 47 137 (1963).

54. J. Cabe et al., EANDC Report, EANDC-49 (1963).

55. R. Wilenzick et al., Phys. Rev., 121 1150 (1961).

56. D. Fossan et al., Phys. Rev., 123 209 (1961).

57. C. Huddleston et al., Phys. Rev., 117 1055 (1960).

58. H. Willard et al., Oak Ridge Natl. Lab. Report, ORNL-2501 (1958).

59. E. Bennett et al., Bull. Am. Phys. Soc., 2 232 (1957).

60. R. Bondelid et al., Phys. Rev., 105 193 (1957).

61. R. Becker et al., Phys. Rev., 102 1384 (1956).

62. M. Walt et al., see Ref. 37.

63. W. Allen et al., Proc. Phys. Soc., A68 1077 (1955).

64. C. Storrs et al., Phys. Rev., 95 1252 (1954).

65. C. Hibdon et al., Argonne Natl. Lab. Report, ANL-5174 (1954).

66. E. Hafner et al., Phys. Rev., 89 204 (1953).

67. N. Nereson et al., Phys. Rev., 89 775 (1953).

68. H. Dvorack et al., Phys. Rev., 90 618 (1953).

69. R. Henkel et al., Values from the NNDC.

70. W. Good et al., Phys. Rev., 79 917 (1951).

71. C. Freier et al., Phys. Rev., 78 508 (1950).

72. D. Miller, Phys. Rev., 78 806 (1950).

73. H. Willard et al., MIT Report, 45 (1950).

74. E. Bretscher et al., Helv. Phys. Acta., A23 15 (1950).

75. R. Fields et al., Phys. Rev., 71 508 (1947).

76. C. Bailey et al., Phys. Rev., 70 583 (1956).

77. D. Frisch, Phys. Rev., 70 589 (1946).

78. J. Whalen et al., data from NNDC and private communication.

79. W. Zinn, Phys. Rev., 56 360 (1939).

80. The Thermal-neutron total cross section was fixed at 4.746 ± 0.25% as given by Francis et al., Proc. Sym. on Neut. Stds. and Flux Normalization, AEC Symposium Series No. 23 (1971) and later re-evaluated by C. Lubitz (private com. 1978).

81. R. Lane and P. Thomas, Rev. Mod. Phys., 30 257 (1958).

82. R. Lane et al., Phys. Rev., 188 1618 (1969), also private communication.

83. R. Holt, Thesis, Yale Univ. (1972); see Nucl. Phys., A213 147 (1973).

84. R. Holt et al., Natl. Bur. of Stds. Pub., NBS-438 (1975).

85. F. Azenberg-Selove, Nucl. Phys. A268 12 (1976).

86. G. Auchampaugh et al., Los Alamos Report, LA-6761 (1977).

87. A. Langsdorf et al., Argonne National Laboratory Report, ANL-5567 (Rev.) (1961); Also private communication.

88. H. Cohen et al., Phys. Rev., 122 534 (1961).