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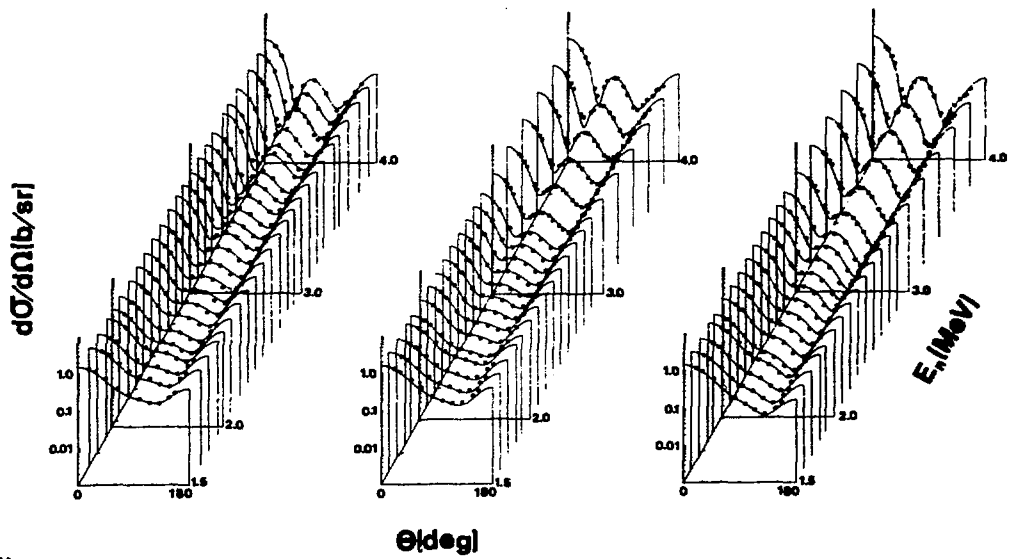

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Neutrons incident on ^{9}Be. Measured σ_t (1 - 10+ MeV), $d\sigma_{el}/d\Omega$ and $d\sigma_{inel}/d\Omega$ (4.5 - 10 MeV). Reaction mechanisms suggested.

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ABSTRACT

Neutron total cross sections of elemental beryllium were measured from 1 to > 10 MeV with good precision. Differential neutron elastic-scattering cross sections were measured from 4.5 to 10 MeV at energy intervals of ≈ 0.5 MeV, and for ≈ 100 angular steps distributed between 18° and 160° at each incident energy. Concurrently, differential cross sections for the emission of a discrete inelastic-neutron group corresponding to an excited level at 2.43 ± 0.06 MeV were determined over the same incident-energy and angular range. Angle-integrated elastic-scattering cross sections were deduced from the observed differential values to accuracies of 2.5%, and angle-integrated inelastic-scattering cross sections were established to accuracies of ≲ 10%. The experimental results are compared with values given in ENDF/B-V, with attention to discrepancies and implications. Qualitative reaction mechanisms are suggested.

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I. INTRODUCTION

For many years beryllium has been used as a neutron multiplier in fission-energy systems, and recently it has been a prominent candidate for enhancing the neutron economy of fusion-energy systems.[1] The latter application has been a matter of recent debate, as the results of some integral experiments indicate multiplication considerably less than is predicted by calculations using accepted evaluated basic-data sets.[2-5] Integral tests can identify overall shortcomings in the fundamental underlying data and/or in its calculational use, but they cannot define microscopic-data problems which may be due to errors in the basic cross sections, the neutron-emission spectra, or both. The definition of these specific issues and their resolution is a microscopic data problem. Despite these uncertainties and the strong interest in beryllium as a neutron multiplier in fusion systems, there have been very few careful experimental studies of the scattering and emission of fast neutrons from beryllium. Drake et al.[6] have measured scattered neutrons and emitted neutron spectra at three energies between ≈ 6-14 MeV. Hogue et al.[7] have measured elastic and inelastic scattering cross sections at nine energies between ≈ 7-15 MeV. There have been several studies near 14 MeV, illustrated by the work of Takahashi et al.[8] Very little is known between the (n,2n) threshold (≈ 1.85 MeV) and 10 MeV, an energy region which will be fairly well-populated in any fusion-blanket containing appreciable amounts of beryllium, and this energy region certainly is a consideration in the interpretation of data from the usual integral tests. The excited level structure of ^{9}Be is reasonably known to about 14 MeV as the result of a number of charged-particle and neutron investigations.[9] There are low-lying levels of both positive and negative parity. Despite this understanding, the reaction mechanism for neutron interaction with beryllium up to 10-14 MeV is not clear. In particular, the strongly inhibited excitation of low-lying positive parity states through the neutron inelastic-scattering process is not explained.

The present work was undertaken in an effort to improve the experimental understanding of the neutron interaction with beryllium in the 1-10 MeV range, and then to test the validity of evaluated nuclear data files currently used in applications. Concurrently, it was hoped to obtain experimental information that would give some guidance as to the fundamental reaction mechanisms involved. Section II deals briefly with the experimental methods used in the measurements, Section III presents the experimental results, and Section IV discusses them in the context of ENDF/B-V. Section IV also considers the qualitative nature of the reaction mechanism governing the inelastic-scattering processes. A topical summary is given in the final Section.

II. EXPERIMENTAL METHODS

The experimental methods employed in the present neutron total and scattering cross-section measurements have been extensively described elsewhere;[10-14] thus, they are outlined very briefly here.

The measurement samples were cylinders of high-purity elemental beryllium (100% ^{9}Be). For the total cross-section measurements, the cylinders were 2 cm in diameter and 1 cm thick, stacked to produce several thicknesses, thereby giving a range of neutron transmissions with a minimum value of ≈ 25%. The neutron beam was incident on the axis of the stacked cylinders. The scattering sample was a cylinder 2 cm in diameter and 2 cm long, with neutrons incident upon the lateral surface. All the cylinders were carefully machined from metal ingots, and the densities calculated from weight and dimension measurements were consistent with those given in the literature.

The neutron source used in the total-cross-section measurements was the $^{9}Be(d,n)^{10}B$ reaction (E_d = 7.0 MeV).[15] This reaction provided an intense white source of neutrons extending from below 1 MeV to well above 11 MeV. The scattering measurements used the $D(d,n)^{3}He$ source, with the deuterium gas contained in a cell ≈ 2.5 cm long at a pressure providing neutron energy spreads at the sample of ≈ 200 keV. The mean neutron energy of the monoenergetic $D(d,n)^{3}He$ source was determined to ≈ ± 10 keV by means of controlling the energy of the incident deuteron beam. Throughout the measurements, the neutron sources were pulsed with burst durations of ≈ 1 nsec. The burst repetition rate in the scattering measurements was 2 MHz, and either that or a lower rate was used in the total cross-section measurements.

The total cross sections were deduced from the measured transmission of the neutrons through the measurement samples.[16] The neutron energy was determined using fast-timing techniques, and a number of sample thicknesses were concurrently studied, using the rotating sample technique described in Ref. 10. A variety of neutron flight paths were used, ranging from ≈ 5 m to ≈ 10 m. Considerable attention was given to background control, and this was verified by concurrent measurements of the well-known carbon total cross section, with results in good agreement with those given in the literature.[17]

The neutron scattering measurements were made using the Argonne 10-angle scattering apparatus.[12–14,18] Measurements were made concurrently at ten scattering angles using flight paths of ≈ 500 cm. The scattered neutrons were observed with liquid-scintillation detectors whose relative energy responses were calibrated using the neutrons emitted from the fission of ^{252}Cf, as described in Ref. 19. The absolute scales of the ten-detector response functions were determined by observing neutrons scattered from the well-known hydrogen standard.[17] All of the scattering measurements were corrected for multiple-event, beam-attenuation and angular-resolution perturbations using Monte-Carlo procedures.[20]

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

In the energy range of the present work (≈ 1–10 MeV), the beryllium total cross section behaves rather smoothly with energy, with only a single large and broad resonance situated at ≈ 2.7 MeV. In this situation, there is no motivation for seeking very fine experimental resolutions, and, thus, instrument scales were selected so that time resolutions of nominally ≈ 3 nsec were obtained. Combined with the flight paths cited above, these provided energy resolutions considerably better than any known structure in the cross section. The neutron energy scale was determined from the measured neutron flight times and flight paths, and verified by the identification of a number of prominent resonances in the neutron total cross section of carbon.[17] The ^{9}Be(d,n) source is extremely intense, particularly for neutron energies $\lesssim$ 6 MeV.[18] As a consequence, counting statistics were very good up to at least 7 MeV. In order to avoid deadtime distortions due to the high response rates, random signals were inserted into the measurement system in such a manner as to give a reliable measure of deadtimes. The geometry was very good; thus, inscattering corrections were negligible. In addition, the beryllium total cross sections were measured at selected energies using conventional monoenergetic-source techniques in order to verify the white-source results with a different method where background control is better assured. The measurements were made in a concurrent manner with several sample thicknesses providing transmissions ranging from ≈ 25-75%. Results obtained with the different sample thicknesses were combined to obtain the results shown in Fig. 1. Since the resolutions were better than the physical structure, self-shielding effects should be negligible. The statistical accuracies associated with the individual datum points range from less than 1% to several percent. Identifiable systematic uncertainties (e.g., sample densities) should be considerably smaller.

Figure 1 shows the comparable cross sections given in ENDF/B-V.[21] The agreement between the present experimental results and the evaluation is generally very good, even through the ≈ 2.7 MeV resonance area where the comparison is sensitive to the exact energy scales. However, in the ≈ 3.2-4.5 MeV region, the present results are noticeably larger than the values of ENDF/B-V, by up to ≈ 4-5%, which is considerably beyond the known experimental uncertainties. It seems that the ENDF/B-V total cross sections are essentially based upon the work of Schwartz et al.[22] That set of measurements is very detailed, and the stated uncertainties are small. However, there are two other relatively recent, comprehensive sets of beryllium total cross section data, those of Auchampaugh et al.[23] and Foster and Glasgow.[24] These two data sets, in the above-cited 3.2-4.5 MeV region of discrepancy, are in good agreement with one another, and with the present results. Thus, in the 3.2-4.5 MeV region, three reasonably contemporary sets of data are consistent with one another, and they are significantly larger than the experimental values of Ref. 22 or the ENDF/B-V evaluation. In this modified form, the evaluation is believed to be accurate to at least ≈ 1.5% from 1-10 MeV. This uncertainty estimate is supported by an independent comprehensive statistical evaluation by one of the present authors (MS), to be reported elswhere.[25] Interestingly, the latter evaluation tends to follow ENDF/B-V in the 3.2-4.5 MeV region of discrepancy. This happens because the large amount of data (with cited good precisions) from Ref. 22 dominated the statistical evaluation procedures. Such a consequence is illustrative of the problem of using statistical evaluation methods to treat discrepant data sets, particularly where the systematic uncertainties are essentially unknown or are underestimated, as apparently has happened in this case. Judgement remains an inherent part of the evaluation process.

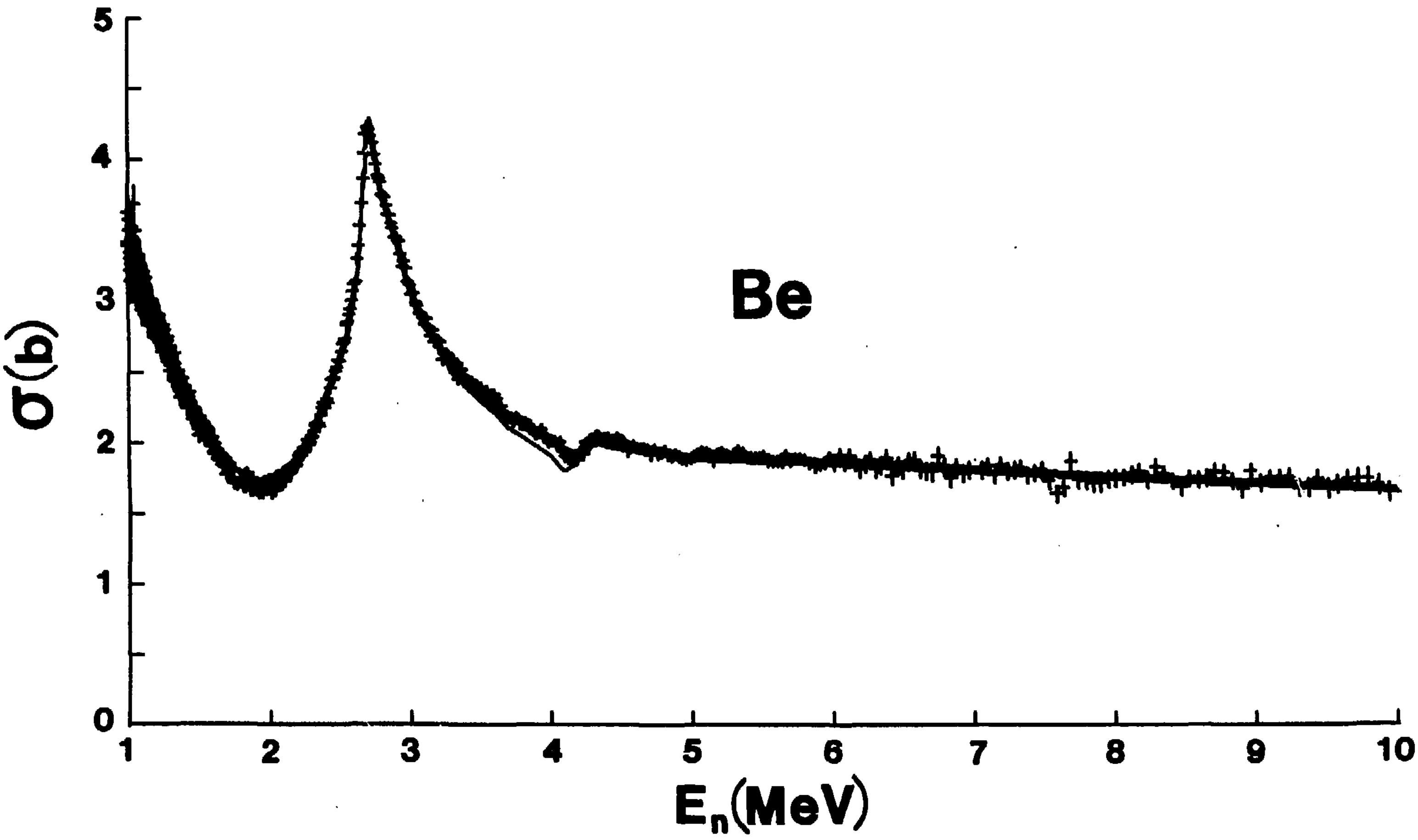

Fig. 1. Neutron total cross sections of beryllium. The present experimental values are noted by "+" symbols. The light curve is ENDF/B-V,[21] and the heavy curve ENDF/B-V, modified as suggested in the text.

B. Neutron Elastic-Scattering Cross Sections

The elastic-scattering measurements were made at angles distributed between ≈ 18° and 160°, from incident energies of 4.5 to 10.0 MeV at increments of ≈ 0.5 MeV. Incident-neutron energy spreads varied from ≈ 200 keV at 4.5 MeV to ≈ 100 keV at 10 MeV. Scattered-neutron energy resolutions were more than sufficient to resolve the elastic-scattered component from inelastically scattered contributions due to the excitation of known states in ^{9}Be.[9] The observed elastically scattered time-of-flight peak was very prominent at all scattering angles and energies, and it was not noticeably perturbed by any other neutron contributions. The target, ^{9}Be, is light; therefore, neutrons emitted from the sample after multiple elastic collisions can be significantly degraded in energy. The consequence is a small "tail" on the prominent elastically scattered peaks observed in the measurements. Monte-Carlo correction procedures simulated this perturbation and provided appropriate correction factors. At each measurement period, between twenty and forty differential cross sections were determined at a given incident energy, and there were at least four measurement periods for every incident energy, distributed over several years. The measured results at each incident energy were combined into a single distribution containing ≈ 100 differential cross sections. The minimum number was ≈ 75 differential values, and the maximum over 150. To a very large degree, the results from the different measurement periods are independent; thus, their combination provides a realistic measure of statistical and systematic uncertainties that is not available from single measurements. The only known common systematic factors between the results obtained at different times are associated with the sample density, which was carefully determined to fractional-percent accuracies, and with the Monte-Carlo multiple-scattering correction procedures,[20] which have been carefully developed and tested over a number of years. The beryllium measurements were generally made concurrently with other scattering measurements, particularly scattering from carbon. The resulting differential elastic- and inelastic-scattering cross sections of carbon were in good agreement with those reported in the literature,[17] both in cross-section magnitude and scattered-neutron energy scale.

The experimental elastic-scattering results are summarized in Fig. 2. There are over a thousand datum values shown in these distributions. A more detailed illustration of a representative distribution is given in Fig. 3. In this example, one can see that the results obtained from the various measurement periods, four in this case, are consistent within the respective experimental uncertainties. The latter are attributed to several sources. There are statistical uncertainties due to counting the scattered particles, both from the beryllium sample and the hydrogen standard, including foregrounds and backgrounds. They were propagated through the data-reduction procedures and are relatively small (from fractional percent to several percent), as the scattered-neutron intensities were good in these measurements and the elastic-scattering cross sections of beryllium are relatively large at all measurement angles. The uncertainties in the H(n,n) scattering standard are very small (a percent or less) at the energies of the present experiments. The relative measurement angles were very carefully determined using conventional optical instruments, and their uncertainty has

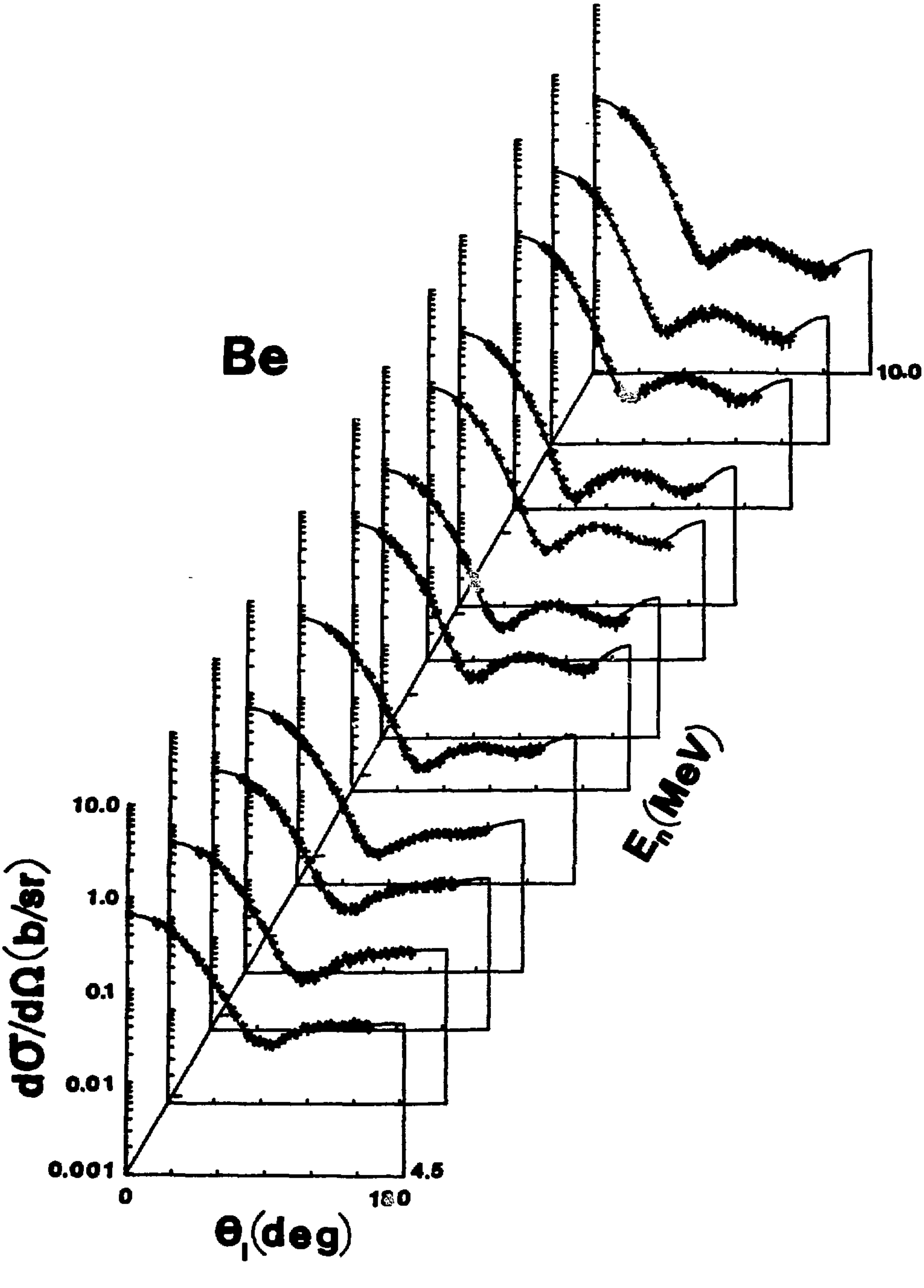

Fig. 2. Differential elastic-scattering cross sections of beryllium. The present measured values are indicated by "+" symbols, and the curves indicate the results of a P_6 fit of Eq. 1 to the measured values. The results are shown in the laboratory coordinate system.

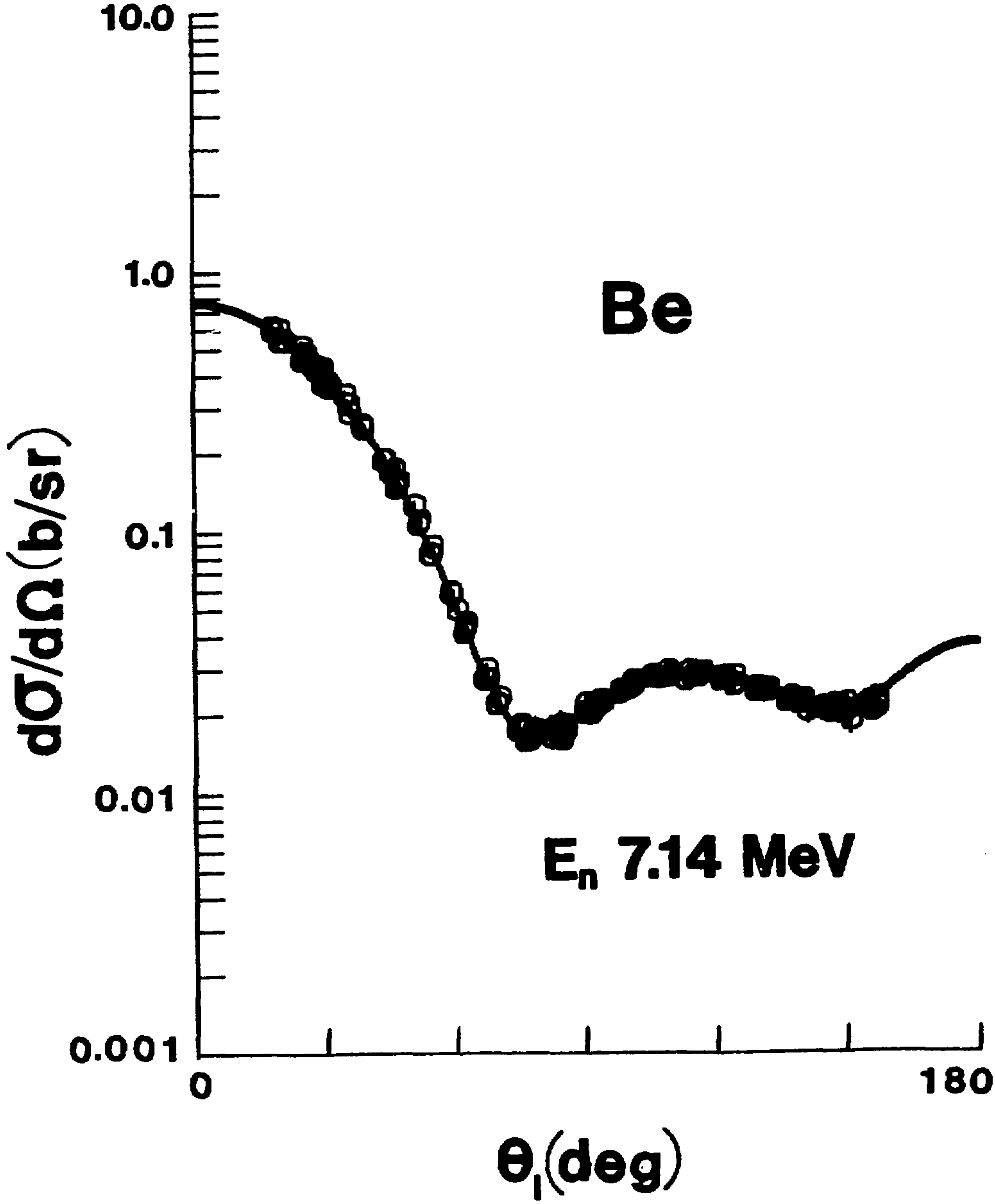

Fig. 3. A detailed illustration of the elastic scattering of 7.14 MeV neutrons from beryllium. The present experimental values are indicated by "O" symbols, and the curve shows the P_6 fit of Eq. 1 to the measured values. The results are given in the laboratory coordinate system.

a negligible effect on the measured results. The normalizations of the relative angular scales were determined by observing the elastic scattering of neutrons from a heavy target (usually niobium) both left and right of the apparent 0° line, at angles where the respective elastic-scattering cross section of niobium (or similar sample) is rapidly changing with angle. It is believed that this procedure determined the zero point of the angular system to within several tenths of a degree. Moreover, these angular calibrations were repeated at each measurement period, and the variations should be random with time. The effect of angle uncertainty was incorporated in the experimental error estimate but was not large, as the beryllium distributions are not as angular dependent as those of a heavier target.

The Monte-Carlo calculations used to correct the measured values for multiple-event, neutron attentuation and angular-resolution effects were pursued through three iterations with a large number of histories (typically 5×10^6 or 1×10^7), resulting in calculational statistical uncertainties of less than 1%. Moreover, the beryllium elastic distributions are not nearly as anisotropic as those of a heavier target and, thus, the Monte-Carlo corrections are more easily carried out to good statistical accuracy. As in all observations, there may be unidentified sources of uncertainty. It was assumed that the latter unidentified contributions amounted to 1.5 mb/sr. The neutrons scattered from the beryllium and the hydrogen standard appear at different energies. Accordingly, the results depend upon the knowledge of the relative energy sensitivities of the individual detectors. The uncertainties in these relative sensitivities are difficult to quantify but are believed to be small (on the order of several percent), and they should be randomly distributed from one measurement to the next. The various uncertainty components were combined in quadrature. Finally, it was subjectively assumed that the minimum overall uncertainty associated with a differential value is ≈ 3% (reflecting possible unidentified systematic uncertainties associated with the detector calibrations), and that became the maximum uncertainty limit in many cases. The measured values are consistent with these uncertainty estimates, as shown in Fig. 3, and one should again remember that this typical example consists of the accumulation of data from four independent measurement periods.

The angle-integrated elastic-scattering cross sections were deduced from the present measurements by least-square fitting the measured values with Legendre-polynomial expansions given by

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}\left[1 + \sum_{i=1}^{n} \omega_i P_i\right] , \qquad (1)$$

where P_i is the i^{th} Legendre polynomial, and n was taken to be 6 or 8. The results obtained with n equal to 6 or 8 agreed to within better than 1%. The value n = 8 was used to obtain the cross sections shown in Fig. 4. The uncertainties associated with the angle-integrated elastic-scattering cross sections were believed to be ≈ 2.5%. That value was arrived at by fitting

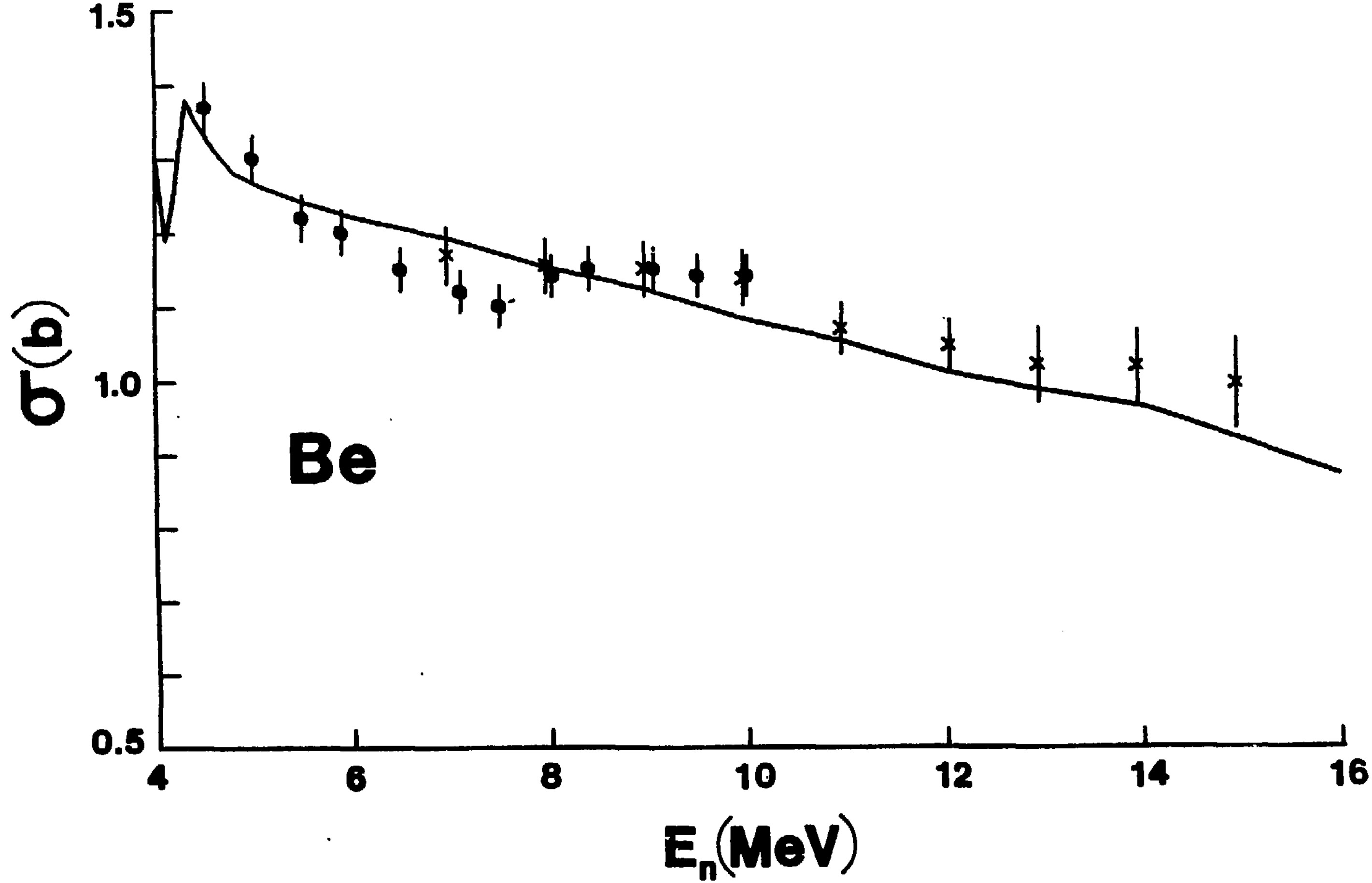

Fig. 4. Comparison of the angle-integrated elastic-scattering results implied by the present work (●) and by the measurements of Hogue et al. (X),[7] with the values given in ENDF/B-V (curve).

the experimental results of each measurement period with Eq. 1 and comparing the resulting angle-integrated cross section values. There were enough independent measurement periods to give a reasonable sample of the uncertainty in the angle-integrated values. Uncertainties obtained from the least-squares fitting procedure alone were generally smaller; thus, the 2.5% estimate is believed to be conservative.

There are some other comparable elastic-scattering measurements reported in the literature. Perhaps the better and more comprehensive of these is the work by Hogue et al.[7] These authors report four values in the present measurement range, and their work extends to higher energies (to ≈ 15 MeV). Hogue et al. give their experimental results as coefficients of a Legendre-polynomial expansion in the center-of-mass system. When the present results are converted to the center-of-mass system and refitted with Legendre-polynomial expansions, coefficients very similar to those given by Hogue et al. are obtained. Furthermore, the graphical distributions given by Hogue et al. look very similar to the present experimental results. The resulting angle-integrated elastic-scattering results are compared in Fig. 4. The agreement between the present work and that of Hogue et al. is remarkably good. All of the values are consistent within the respective uncertainties, and for three of the four comparable energies, the agreement is nearly exact (far better than should be expected from the respective uncertainties). Drake et al.[6] have reported elastic scattering results at ≈ 6, 10, and 14 MeV. Their angle-integrated elastic-scattering results are in very good agreement with those of the present work, but their uncertainties exceed 10%. Figure 4 also compares the present results, and those of Hogue et al., with the elastic-scattering cross section given in the evaluation of ENDF/B-V.[21] The measured and evaluated results are somewhat different in both shape and magnitude. The implication of these differences will be discussed in Sec. IV, below.

C. Neutron Inelastic Scattering

There are seven levels in ^{9}Be that are energetically available for inelastic scattering at the energies of the present experiments;[9] 1.69 MeV ($1/2^+$), 2.429 MeV ($5/2^-$), 2.8 MeV ($1/2^-$), 3.05 MeV ($5/2^+$), 4.70 MeV ($3/2^+$), 6.76 MeV ($7/2^-$), and 7.94 MeV ($1/2^-$). The latter three were not examined, as the respective levels are broad and the resulting inelastically-scattered neutrons have relatively low energies. As a consequence, the emitted neutrons are lost in a continuum spectrum of neutrons emitted in (n,2n) and other breakup reactions. The observed time-of-flight spectra in the region of the first four levels consisted of a broad "hump" of emitted neutrons on which was superimposed a well-resolved and prominent discrete inelastic-neutron group corresponding to an observed excitation of 2.43 ± 0.06 MeV. The underlying "hump" was angular dependent, and, at higher energy, was peaked in the forward direction. At all but the most forward scattering angles, the experimental resolution was sufficient to observe neutrons resulting from the inelastic excitation of the 1.69 MeV level, even given its rather broad width of $\Gamma \approx 210$ keV.[9] Early photo-emulsion studies[26] at incident energies of ≈ 3 MeV qualitatively indicate some inelastic neutrons due to the excitation of the 1.69 MeV level, but there was no evidence for such a contribution in the present measurements. If such a component is present, it must have a very small cross section. The second level at 2.429 MeV is reported[9] to have a rather narrow width and closely corresponds to the very prominent inelastic-scattering group observed in the present measurements. The 2.8 MeV level is very broad[9] ($\Gamma \approx$ 1.1 MeV). In the present experiments, it would be impossible to distinguish any corresponding inelastically scattered neutrons from the general broad continuum distribution cited above. The 3.05 MeV level is also comparatively broad ($\Gamma \approx$ 300 keV), and is centered only about 600 keV above the 2.429 level. This relatively close spacing and broad width make it difficult to resolve it from the contribution due to the prominent 2.429 MeV level. Inelastic excitation of the 3.05 MeV has been reported,[6] but at intensities much below that due to the 2.429 MeV level. In the present work there was some indication of a weak inelastic contribution due to the excitation of the 3.06 MeV level, particularly at the larger scattering angles. However, it was of very low intensity and not well defined.

In view of the above situation, the present measurements gave emphasis to determining the inelastic-scattering cross section due to the excitation of the 2.429 MeV level. It was assumed that the continuum emission contribution underlying the prominent experimental peak, including possible artifacts due to the 3.06 MeV level, could be subtracted by linearly extrapolating between the two shoulders of the prominent peak. Subjective judgements were involved in the determination of the shoulder points to be used in the extrapolation, particularly with respect to the lower-energy side of the peak. At different times, these judgements were independently made by two of the authors (MS and AS), with results that were relatively consistent. The objective was always to obtain the contribution attributable to the 2.429 MeV level as free from other components as possible.

The experimental inelastic-scattering results, obtained using the above procedures, are summarized in Fig. 5, and a detailed drawing of one of these distributions is shown in Fig. 6. Each distribution contained a minimum of approximately forty points, and the maximum number exceeded one hundred. Each illustrated distribution is the combination of the results of three or more measurements taken over a several-year period with, as for the elastic-scattering cited above, different instrumental arrangements. The results obtained during the different measurement periods should be essentially independent, and, thus, reproducibility is an indication of uncertainty. The uncertainties attributed to the individual datum points varied a great deal, depending upon the particular energy, angle, and experimental conditions, with the components outlined above in the context of elastic scattering. However, a minimum systematic uncertainty of 10% was assigned to all the measured values as a subjective estimate of uncertainties involved in the above-outlined continuum-subtraction and -summing procedures. At large scattering angles and lower energies, the experimental uncertainties can considerably exceed this minimum value. This increase is due to counting statistics and to the same minimum uncertainty of 1.5 mb/sr, as accepted for the elastic-scattering measurements. As is illustrated in Fig. 6, the data are consistent to well within the uncertainty estimates.

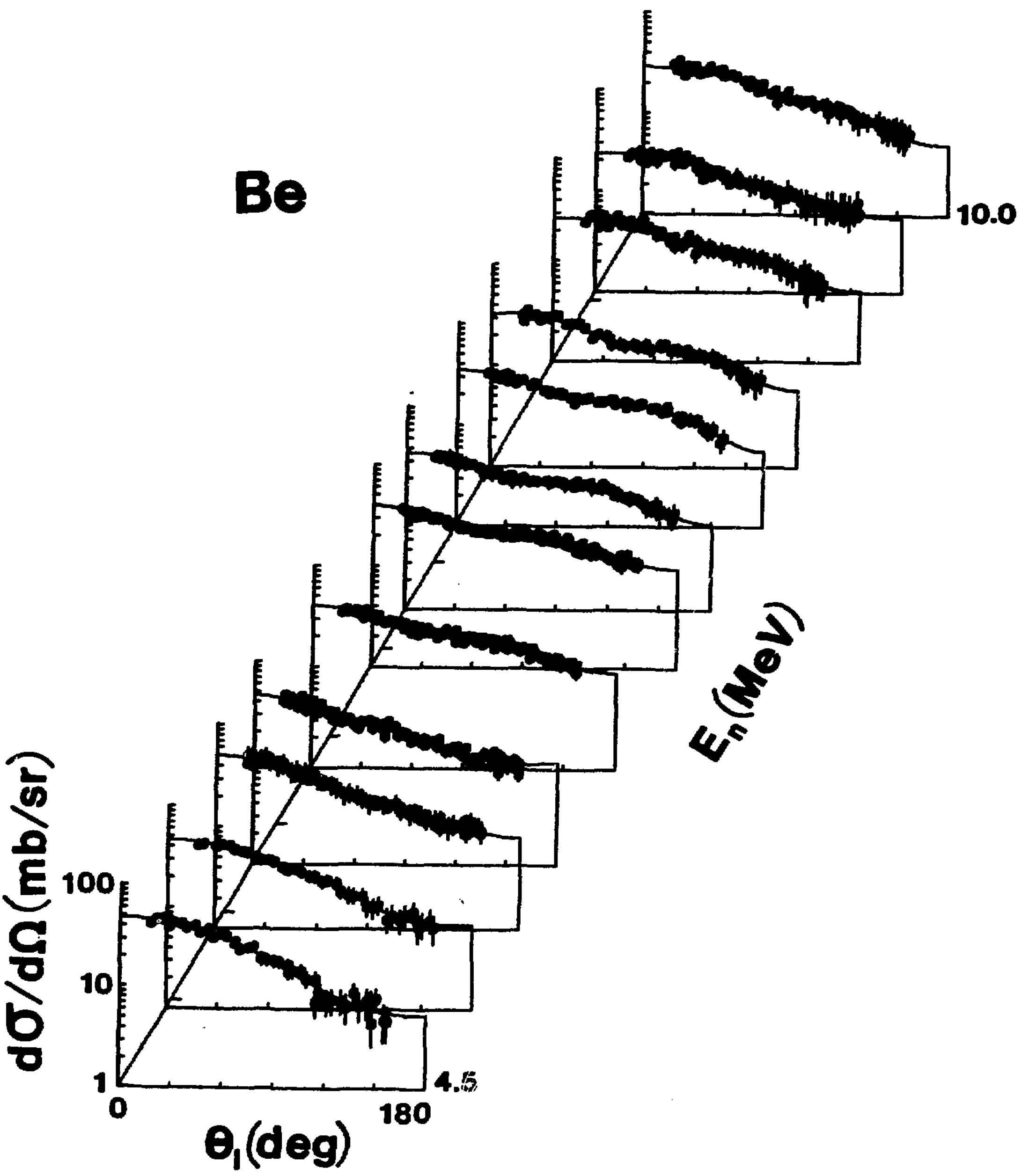

Fig. 5. Neutron differential cross sections for the excitation of the 2.429 MeV level in ^{9}Be. The present measured values are indicated by "O" symbols, and the results of fitting Eq. 1 to the data are represented by the curves. The data are given in the laboratory coordinate system.

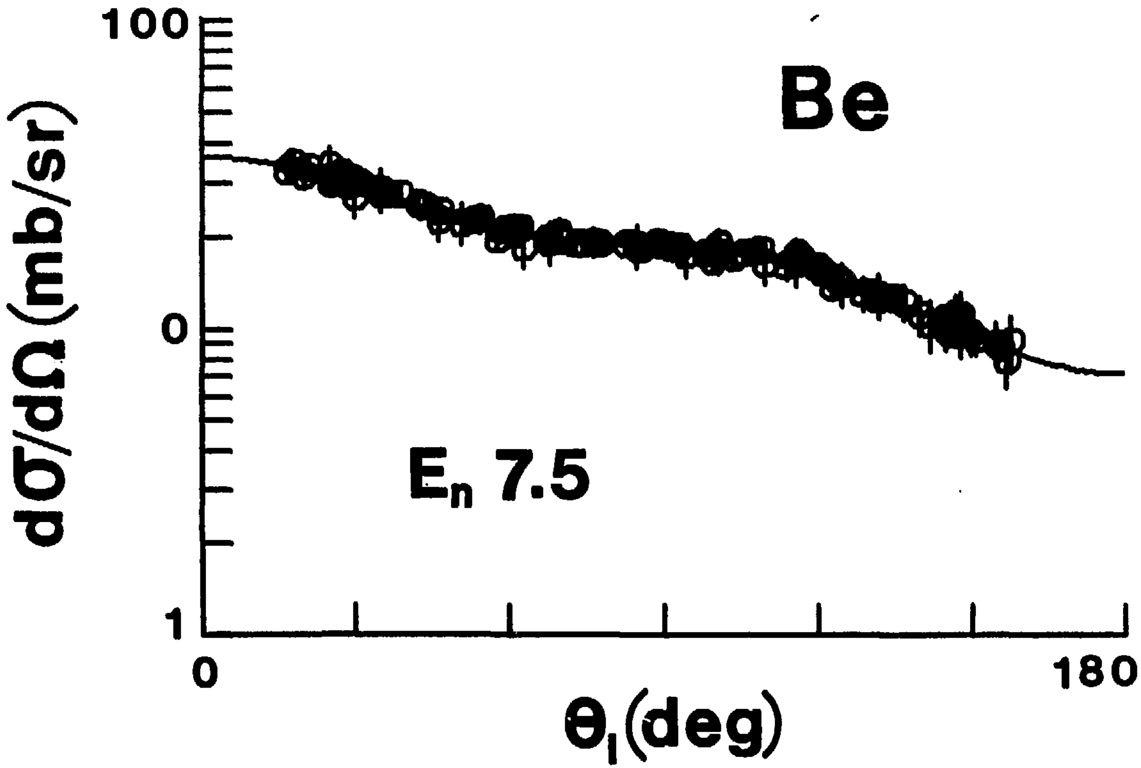

Fig. 6. Differential cross sections for the excitation of the 2.429 MeV level in ^{9}Be by 7.5 MeV incident neutrons. The measured values are indicated by "O", and the result of a fit of Eq. 1 to the data is represented by the curve. The quantities are given in the laboratory coordinate system.

The angle-integrated cross sections for the excitation of the 2.429 MeV level were deduced from the measured differential values by again least-square fitting Eq. 1 to the measured differential quantities, using a value of $n = 6$. The results of the fitting were descriptive of the measured values, as shown by the curves in Fig. 5. The deduced angle-integrated values are shown in Fig. 7. Their estimated uncertainties are 10%, reflecting the above-mentioned subjective estimates used in the summing procedures. Statistical and other error sources are generally much smaller, and the angle-integrated values obtained from results of different measurement periods are generally consistent to well within the 10% estimate. Figure 7 also shows the results reported by Hogue et al.[7] and by Drake et al.[6] The latter values are somewhat larger than the present results, or those of Ref. 7, but have uncertainties of 20-30%. The results of Hoque et al. are systematically larger than the present results, but are only slightly beyond the respective experimental uncertainties, if that. The results of Ref. 7 explicitly include any possible contribution from the 3.06 and 1.69 MeV levels. Therefore, the cross sections should be somewhat larger than those of the present work (by an amount reflecting the two possible additional contributions), which sought to define the inelastic-scattering due to the excitation of the 2.429 MeV level alone. It is interesting that the energy-dependent shapes of the present data and those of Hogue et al. are very similar, even to the small discontinuity in the region of 10 MeV. Figure 7 also shows the comparable inelastic cross section as given in ENDF/B-V.[21] It is much larger than the present measured values, or those of Hogue et al., by a factor of up to nearly two. This discrepancy is discussed in Sec. IV, below.

IV. DISCUSSION

The present total cross section measurements, and an evaluation by one of the authors (MS),[28] support the ENDF/B-V[21] total cross sections over a very large portion of the region of the present scattering measurements (≈ 5-10 MeV). The evaluation, and a detailed inspection of the general total cross section data base, indicate that the uncertainties to be associated with the ENDF/B-V total cross sections are, conservatively, ≈ 1.5% or less from ≈ 5-10 MeV. Therefore, the ENDF/B-V total cross sections, with uncertainties of 1.5%, were assumed for the following discussion. The numerical values at the energies of the present scattering measurements are given in Table 1. The same table gives the corresponding angle-integrated elastic-scattering cross sections deduced by Legendre-polynomial fitting the present data, as described in Sec. III-B. The RMS difference between the measured elastic-scattering cross sections and those given in ENDF/B-V is ≈ 4%, with a systematic trend for the evaluated quantities to be 3-5% larger in the middle of the energy range, and nearly the same amount smaller at the upper and lower extremes of the energy range. The differences, while not large, are probably real, as they are approximately twice the experimental uncertainties and are systematic with energy. The nonelastic cross sections ($\sigma_{nonel} \approx \sigma_t - \sigma_{el}$) implied by the measured elastic-scattering cross sections and the total cross sections are also given in Table 1. Of course, they are different from those implied by ENDF/B-V by amounts reflecting the above-cited differences in the elastic-scattering cross sections.

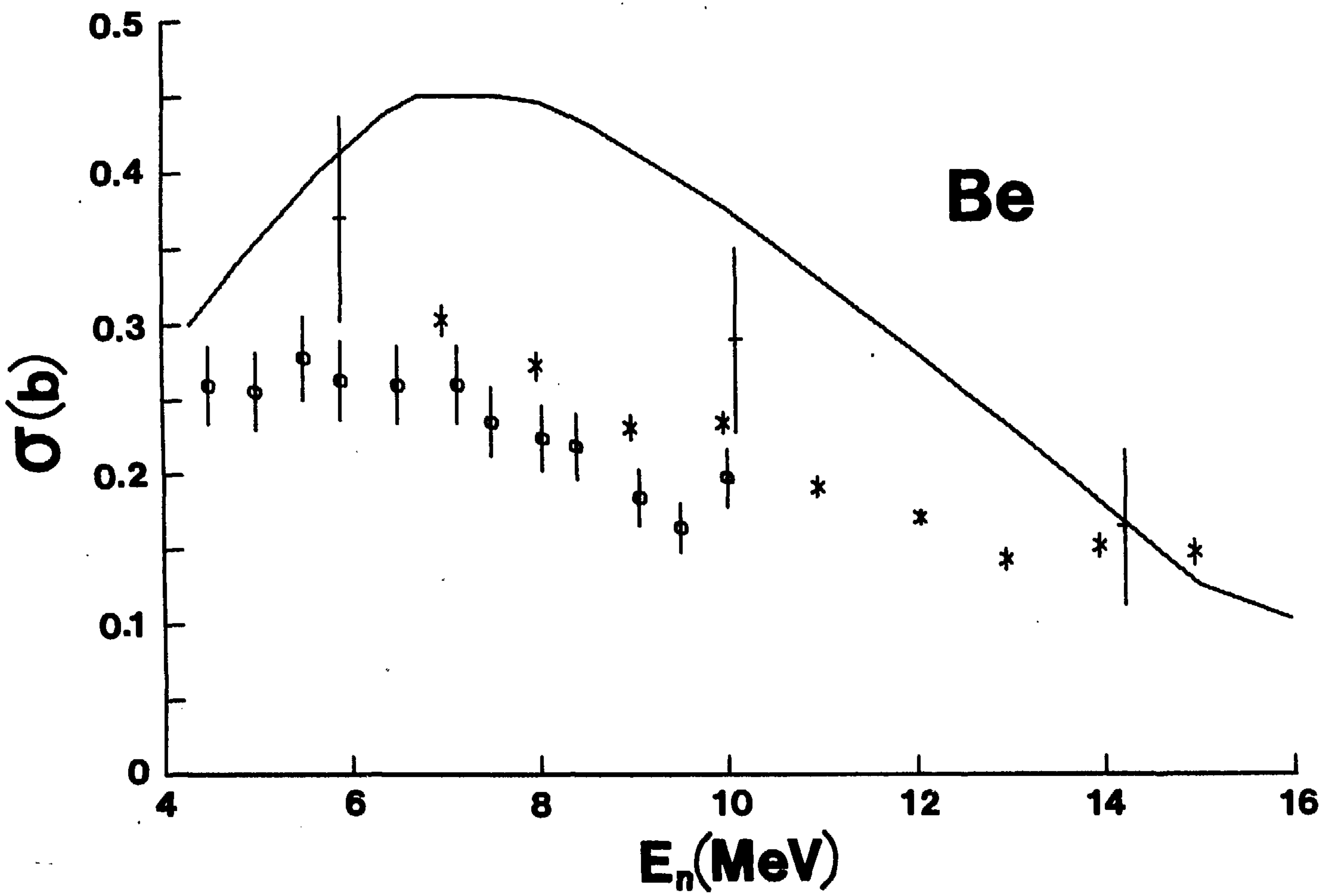

Fig. 7. Angle-integrated cross sections for the excitation of the 2.429 MeV level in ^{9}Be. The presently measured values are indicated by "O" symbols, those of Ref. 6 by "+", and of Ref. 7 by "X". The curve indicates the comparable quanitites given in ENDF/B-V.[21]

Table 1. Comparative Measured and Evaluated Neutron Cross Sections of Beryllium

Reaction		Incident Neutron Energy in MeV											
		4.5	5.0	5.5	5.9	6.5	7.14	7.5	8.03	8.4	9.06	9.5	10.0
σ_T(b)[a,b]		1.9454	1.8886	1.8680	1.8528	1.8286	1.7969	1.7757	1.7532	1.7361	1.7114	1.6882	1.6651
		(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)	(1.5%)
σ_{el}(b)	Exp.[c]	1.370	1.300	1.215	1.200	1.150	1.120	1.100	1.145	1.155	1.150	1.145	1.140
		(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)	(2.5%)
	ENDF/B-V[d]	1.330	1.267	1.240	1.224	1.205	1.186	1.170	1.150	1.138	1.120	1.100	1.080
σ_{nonel}(b)[e]	Exp.[c]	0.5754	0.5886	0.6530	0.6526	0.6786	0.6769	0.6757	0.6082	0.5811	0.5614	0.5432	0.5251
		(7.8%)	(7.3%)	(6.3%)	(6.3%)	(5.9%)	(5.8%)	(5.6%)	(6.4%)	(6.7%)	(6.9%)	(7.0%)	(7.2%)
	ENDF/B-V	0.6154	0.6219	0.6280	0.6286	0.6236	0.6109	0.6057	0.6032	0.5981	0.5914	0.5882	0.5851
σ_{inel}(b)[f]	Exp.[c]	0.260	0.256	0.278	0.263	0.280	0.260	0.235	0.224	0.218	0.184	0.164	0.197
		(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)	(10%)
	ENDF/B-V	0.316	0.354	0.389	0.413	0.443	0.450	0.450	0.445	0.434	0.392	0384	0.375
$\sigma_{nonel}-\sigma_{inel}$(b)[g]	Exp.[c]	0.3154	0.3326	0.3750	0.3896	0.4186	0.4169	0.4407	0.3842	0.3631	0.3774	0.3792	0.3281
		(16%)	(15%)	(13%)	(12%)	(11%)	(11%)	(11%)	(12%)	(12%)	(11%)	(11%)	(13%)
	ENDF/B-V	0.2994	0.2678	0.2386	0.2156	0.1806	0.1609	0.1557	0.1582	0.1640	0.1993	0.2046	0.2101
	% Difference[h]	(-5.3%)	(-24%)	(-57%)	(-81%)	(-131%)	(-159%)	(-183%)	(-143%)	(-121%)	(-89%)	(-85%)	(-56%)

[a] Taken from ENDF/B-V assuming 1.5% uncertainty. See text for details.

[b] Uncertainties in percent are given in brackets.

[c] Measurement cross sections determined in present experiments, as relevant.

[d] Elastic cross sections of ENDF/B-V.

[e] $\sigma_{nonel} \equiv \sigma_T - \sigma_{el}$.

[f] Inelastic cross section for excitation of 2.43 MeV level only.

[g] $\sigma_{nonel}-\sigma_{inel}$ (E_x = 2.43 MeV) ≡ remaining partial cross sections, (n,2n), etc.

[h] Defined as (ENDF - EXP)/ENDF in percent.

Table 1 gives the inelastic-scattering cross sections for the excitation of the 2.429 MeV level (σ_{inel}) deduced from the present measurements, as described in Sec. III-C. The respective uncertainties are dominated by the systematic 10% uncertainties conservatively attributed to the summing procedures outlined in Sec. III-C. The table also gives what seem to be the comparable values from ENDF/B-V. The latter are larger than those deduced from the measured values by factors ranging from ≈ 1.2 to more than 2. These are large differences in cross sections that are a substantive fraction of the total nonelastic cross section, and well beyond the uncertainties of the present experimental results. The situation does not substantively change if one considers the alternate experimental results of Hogue et al.[7] These differences are also clearly evident in Fig. 7. The experimental measurements also imply the totality of partial nonelastic cross sections, exclusive of the inelastic cross sections for the explicit excitation of the 2.429 MeV level ($\sigma_{part} \equiv \sigma_{nonel} - \sigma_{inel}$). Those partial cross sections include a number of reaction channels, in particular contributions to the (n,2n) reactions. The corresponding experimentally deduced quantities are given in Table 1. The uncertainties are in the range 11-16%. The comparable ENDF/B-V values systematically vary from reasonable agreement at the lowest energies (≈ 5%, the low-energy value must be taken with caution due to the σ_t discrepancy noted above) to very large differences at the higher energies, with the experimentally deduced values more than a factor of 2.5 larger at some energies, and, generally, approximately a factor of 2 larger over a major portion of the energy range. Moreover, the experimentally deduced cross sections are large, ≈ 20% of the total cross section. Clearly, the present measurements suggest some rather significant discrepancies with the ENDF/B-V partial cross sections, and these may be reflected in integral energy-transfer mechanisms. The implication of these differences may be considerable in some applications, but the details will depend on the exact nature of the other partial cross sections, particularly the continuum neutron-emission processes.

As noted in Section III-C, above, the inelastic-neutron excitation of the first excited state at 1.69 MeV ($1/2^+$) is very weak and was not observed in the present measurements. The next positive parity state (3.05 MeV, $5/2^+$) is also very weakly excited, while, at the same time, scattering to the odd parity states is prominent (ground state, $3/2^-$, and 2.429 MeV, $5/2^-$, level). This suggests a possible shape "co-existence" in the ^{9}Be nucleus. The Nilsson diagram for the lightest nuclei suggests that the last neutron in the ground-state ($J^\pi = 3/2^-$) configuration of ^{9}Be should lie in the $[101\ 3/2]$ orbit (stemming from the $1p_{3/2}$ state of the spherical potential), and, to be energetically favorable, should tend to push the nucleus towards a spherical shape. The first-excited state ($J^\pi = 1/2^+$) should, on the other hand, have its final neutron in the $[220\ 1/2]$ orbital (from the $1d_{5/2}$ state), which, to favor energy, will tend to push the nuclear shape towards large prolate deformation. The very low excitaion of this state (1.69 MeV) certainly favors this interpretation, and its large width ($\Gamma \approx 200$ keV) also indicates the large deformation preceding breakup into the two α-particles underlying the ^{8}Be core structure. Most of the higher states appear to be interpretable as rotational bands, with these first two states as band heads. Thus, the second excited state (2.429 MeV, $5/2^-$) appears to be the first rotational level built upon the ground state, while the $5/2^+$ state at 3.05 MeV, and probably the $3/2^+$ state at 4.7 MeV, could be members of a decoupled band based upon the 1.69 MeV state. If such interpretations are correct, the rotational moment-of-inertia parameters of the bands are, respectively, $\hbar^2/2I \approx 0.5$ MeV and 0.34 MeV, again indicating a much greater deformation for the 1.69 MeV state than for the ground state.

The interaction of an incident neutron in the zero to several-MeV range with the ^{9}Be ground state will develop through states that can be described as a single-particle neutron orbiting in the field of the near-spherical ^{9}Be $3/2^-$ core. The relevant single-particle orbits will be those Nilsson orbits developing from the spherical $2s_{1/2}$ and $1d_{3/2}$ states, and, to a much less extent, from the $1d_{5/2}$ state. The predominant total J^π values concerned are 1^- and 2^-, to a lesser extent 0^- and 3^-, and to a small degree 4^-. These states have little similarity to the configurations required to give a significant reduced neutron width for emission to the first-excited state of ^{9}Be. For $J^\pi = 0^-$, 1^-, and 2^- states, the $[101\ 3/2]$ and $[101\ 1/2]$ orbitals (both lying much lower than the s and d orbitals) are required, and for the $J^\pi = 0^-$ and 1^- states alone, the $[330\ 1/2]$ orbit stemming from the $1f_{7/2}$ spherical state will be involved. Because of the large deformation expected for the ^{9}Be excited core, this last orbit can be expected to lie in the same energy region as the 2s and 1d orbitals. This alone could favor relatively strong mixing of "initial" and "final" configurations. However, against such mixing, one could expect the rather large difference in core deformation to provide a decisive hindrance factor. Thus, one expects the states strongly excited by neutron absorption in ^{9}Be to have weak reduced widths for neutron reemission to the first excited state. In contrast, the configurations involved in neutron emission to the second excited state are expected to be mixed strongly, through rotational coupling, with those invoked in the initial neutron absorption mechanism.

V. SUMMARY

The present neutron total-cross-section measurements support the ENDF/B-V[21] evaluation from 1-10+ MeV, excepting a local region between approximately 3.2 and 4.5 MeV where the present experimental values, and those in the literature, suggest that the evaluated total cross sections should be increased by up to ≈ 5%. The present measurements give new definition to the differential and angle-integrated elastic- and inelastic-scattering cross sections over the incident energy range 4.5-10 MeV. The experimental elastic-scattering results differ modestly from those given in ENDF/B-V. They have been used in upgrading the evaluated elastic-scattering cross sections of the proposed ENDF/B-VI, as illustrated by the comparisons of Fig. 8.[27] The cross sections for the inelastic-neutron excitation of the 2.429 MeV level were determined with results that disagree with those apparently given in ENDF/B-V by up to a factor of approximately two. These are large differences in a cross section that is a significant part of the total cross section. The experimental results imply that the remainder of the nonelastic cross section, exclusive of the excitation of the 2.429 MeV level, are very different from those given in ENDF/B-V (by a factor of two or more) over the large majority of the the 4.5-10 MeV measured energy range. Such differences can be a serious concern in a diversity of applications to fusion- and fission-energy systems which rely upon neutron multiplication in beryllium for viability. The details of this concern depend upon the character of the various partial cross sections and the associated emission spectra, which are not well known. The quantitative nature of the nuclear processes governing the interaction of fast neutrons with ^{9}Be are not well understood. It is suggested that, qualitatively, the processes leading to the excitation of the ground and low-lying states are governed by two rotational bands based upon the negative-parity ground state and the positive-parity first-excited (1.69 MeV) state, in a manner that strongly inhibits inelastic-neutron excitation of the positive-parity levels. The concepts are consistent with the observed results, and with the collective model of Nilsson.

The interaction of fast-neutrons with ^{9}Be remains somewhat of an enigma from both fundamental and applied points of view. Integral studies are useful to test the overall processes, but they will not provide sufficient information to resolve the microscopic physical questions raised above. They are necessary but not sufficient criteria for testing or validating the underlying physical processes. What is needed for applied and fundamental understanding are detailed microscopic experimental and theoretical studies directed toward a comprehensive understanding of the interaction of fast neutrons with ^{9}Be. In particular, these should include precise studies of discrete neutron inelastic scattering and of continuum neutron-emission processes using the best contemporary techniques, extending well beyond the limited objectives of the present work and the information available in the literature. It is indeed remarkable that so little reliable neutron information is available for a nucleus of such interest for important applications.

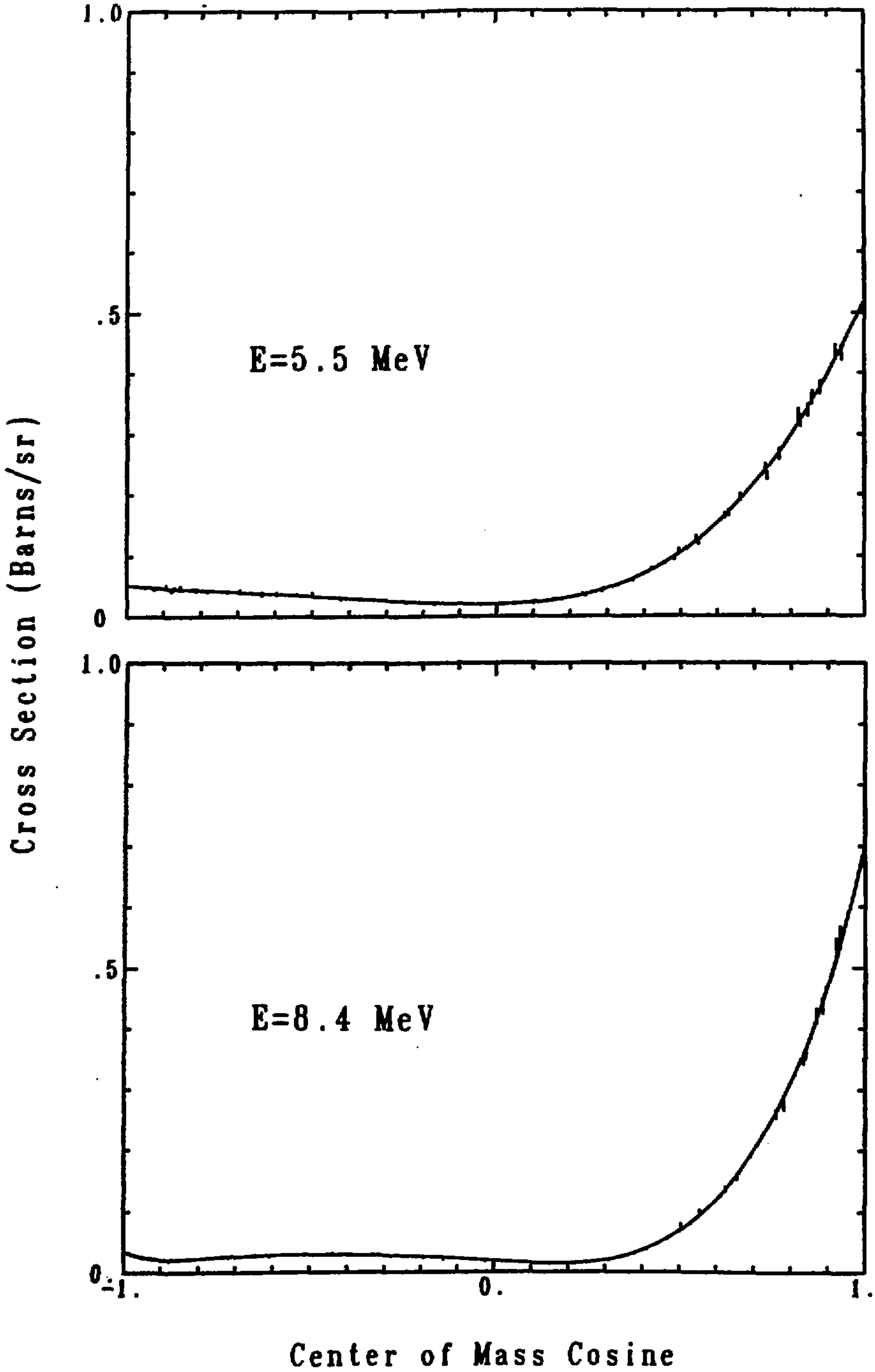

Fig. 8. Illustrative use of the present experimental results to upgrade the proposed ENDF/B-VI ^{9}Be evaluation.[27] The present elastic-scattering results are indicated by vertical bars, the evaluation by the curves. Incident-neutron energies are 5.5 and 8.4 MeV. The data shown are in the center-of-mass system.

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