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NOTE ON THE ELASTIC-SCATTERING OF FEW-MeV NEUTRONS FROM ELEMENTAL CALCIUM*

by

A. B. Smith and P. T. Guenther

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by

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ABSTRACT

Neutron differential-elastic-scattering cross sections of elemental calcium are measured from < 1.5 to 4.0 MeV at intervals of ≈ 50 keV. Scattering angles are distributed between 20 and 160 deg. Incident-neutron energy resolutions are ≈ 50 to 100 keV. The experimental results are compared with values given in ENDF/B-V and are examined in the context of shielding applications. An optical potential is deduced from the measured values and its possible implications are discussed.

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

I. INTRODUCTION

The present experimental study had two objectives: 1) an examination of the optical potential in a region of large compound-elastic scattering (CE), double shell closure and essentially zero iso-vector component, and 2) the provision of angular-distribution information useful in shielding applications. The scattering targets were elemental calcium metal which, for the present purposes, can be considered entirely the doubly-magic nucleus ^{40}Ca. Conventional optical potentials generally include an iso-vector term[1,2] and the imaginary portion of the potentials tends to become small in the region of shell closure.[3,4] Quantitative knowledge of these trends is limited in the few-MeV region generally accessible only to neutron-induced processes. Calcium is a primary constituent of concrete and thus of interest from the point of view of shielding applications. First-order neutron transmission depends only upon the neutron total cross section which is reasonably well known.[5] However, higher-order effects influencing both penetration and reflection are dependent on the scattered-neutron angular distributions. For calcium, these distributions are essentially due to elastic scattering over the several-MeV region. Elastic-scattering cross sections of calcium are known to sharply fluctuate in magnitude and angular dependence with energy throughout the few-MeV region. Previously reported measurements of calcium elastic scattering at these energies tend to be limited to isolated energies. The present measurements were so arranged as to assure continuous energy coverage with an intermediate resolution. These measurements yield a reliable knowledge of the elastic scattering to an intermediate resolution which can be further averaged to even broader resolutions to provide cross sections consistent with the concept of the optical model (OM).

II. EXPERIMENTAL MEASUREMENTS AND RESULTS

All the measurements were made using the Argonne National Laboratory ten-angle time-of-flight apparatus. That apparatus and its application have been described extensively elsewhere and will not be discussed further here.[6] The measurements were made at incident-neutron-energy intervals of $\approx$ 50 keV from < 1.5 to 4.0 MeV with incident-energy resolutions of $\approx$ 50 to 100 keV. The scattered-neutron resolutions were sufficient to resolve the elastic-scattering component from all known inelastic-scattering contributions. Ten differential values were obtained at each incident energy, distributed between 20 and 160 deg. The scattering sample was a 2 cm in diameter and 2 cm long cylinder of calcium metal placed in a stainless-steel can 0.013 mm thick. Identical cans were available for background determinations. The statistical uncertainties of the individual measured values are $\lesssim$ 3%. The scattering angles are known to ± 1 deg. The absolute calibration of the efficiencies of the ten detectors was based upon the <u>total</u> cross section of elemental carbon[7] using the methods described in Ref. 8. The detector efficiencies appeared to be known to ± 3% and were reproducible to that acccuracy. Correction procedures, such as those associated with multiple events, introduced an additional $\lesssim$ 1% uncertainty. Thus, the overall differential-cross-section uncertainty was $\lesssim$ 5%.

The experimental results are summarized in Fig. 1. Strong energy-dependent fluctuations in both magnitude and relative shape are evident. These were smoothed by constructing a 250-keV running average of the measured values to obtain the results shown in Fig. 2. Even with the broad average, the fluctuations persist. The averaged differential cross sections were least-squared fitted with a 6th-order Legendre-polynomial series in order to obtain the angle-integrated elastic-scattering cross sections. The latter are compared in Fig. 3 with the high-resolution elastic scattering values as given in ENDF/B-V.[9] The ENDF/B values very likely overemphasize the fluctuations above the (n;p) and (n;α) thresholds, but generally the present angle-integrated results follow the trends of the high-resolution evaluated data again with persistent fluctuations in the 250-keV averaged quantities. The same fluctuations are evident in the B_ℓ coefficients of the Legendre-polynomial representation of the averaged values, as shown in Fig. 4, and extend through at least the B_4 term.

There have been previous measurements of calcium elastic scattering at comparable energies.[10,11] Generally, the previous results were obtained at isolated energies which makes quantitative comparisons with the present values difficult, or even deceptive, due to the evident fluctuating structure. For example, Reber and Brandenberger[11] have reported results at 2.06 and 3.29 MeV. These two distributions are compared with those obtained in the present work in Fig. 5. At 2.06 MeV, the agreement is not good while at 3.29 MeV it is excellent. This dichotomy points up the importance of energy-comprehensive measurements when dealing with an energy-fluctuating cross section.

III. INTERPRETATION AND COMMENT

The thresholds for (n;p) and (n;α) reactions in calcium are at low energies and the cross sections rise rapidly to a cumulative value of ≈ 0.6 b at 4.0 MeV. Thus, one expects significant compound-nucleus (CN) decay into the charged-particle-emission channels with a corresponding dilution of the compound-elastic (CE) contribution. This eventuality complicates the interpretation of the present results. In addition, obvious large fluctuations of the elastic-scattering cross section over the energy range of the present measurements make it difficult to assure an energy-averaged behavior consistent with the concept of the optical model (OM). Faced with these problems, the OM interpretation of the experimental results was based upon the energy range ≈ 1.5 to 2.6 MeV. It was hoped that this interval was wide enough to provide a reasonable energy average in a region where the (n;p) and (n;α) contributions are yet quite small. The cumulative total of the latter is ≈ 0.1 b at 2.6 MeV and decreases rapidly with decreasing energy. Radiative neutron capture is a negligible perturbation in the present energy range and was ignored.

Calcium is a doubly-magic nucleus and it is thus appropriate to base the interpretation upon a simple spherical OM. CE contributions were large throughout the measured energy range. They were calculated using the statistical model of Hauser-Feshbach,[12] as corrected by Moldauer.[13] All

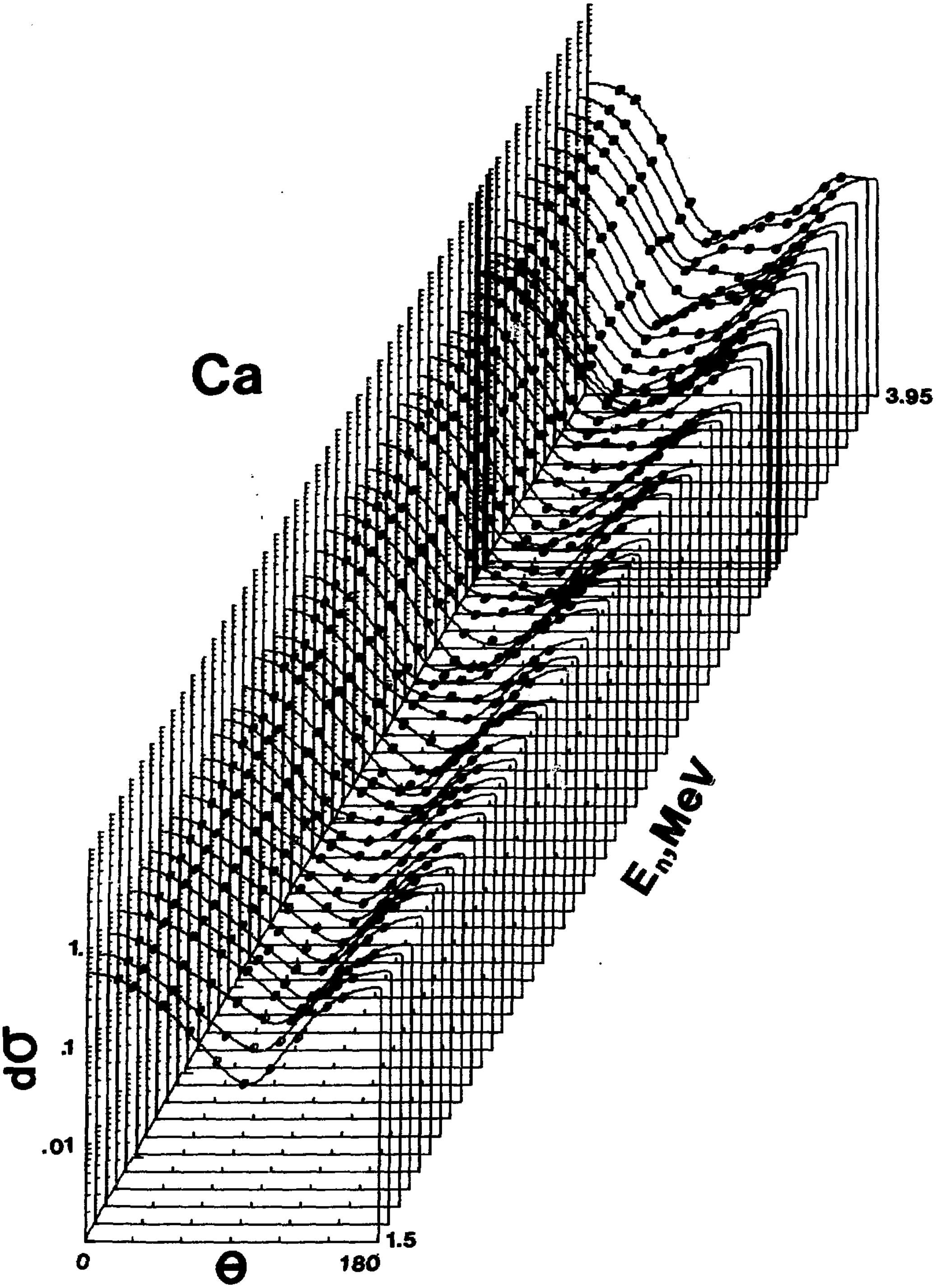

Fig. 1. Differential-elastic-scattering cross sections of calcium. The present experimental values are denoted by data symbols. The curves result from fitting Legendre-polynomial series to the measured values. The dimensionality is scattering angle in deg. and cross section in b/sr expressed in the laboratory system.

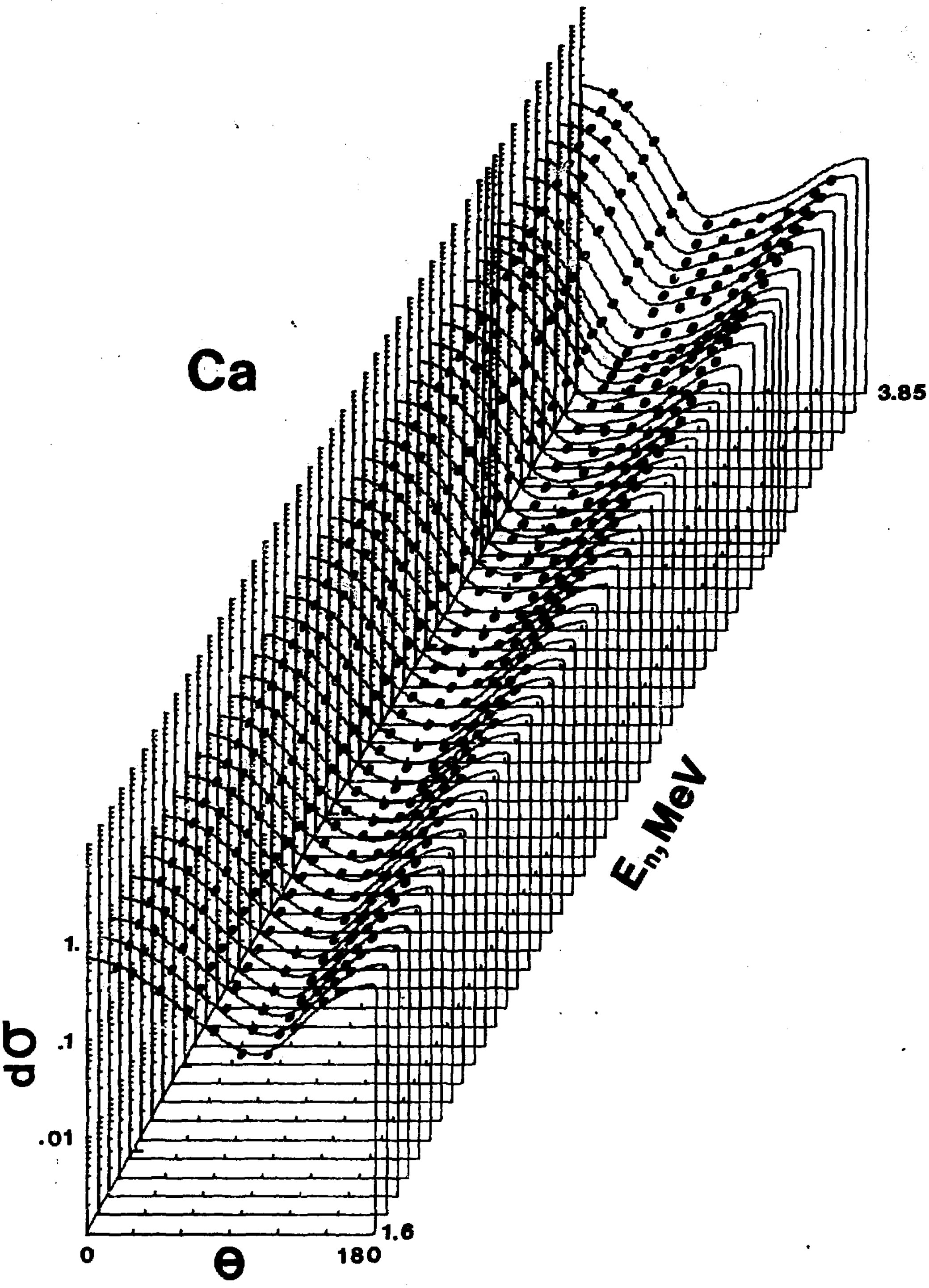

Fig. 2. Differential-elastic-scattering cross sections of calcium. The present experimental results, averaged over 250 keV, are noted by data symbols. Curves indicate the results of model calculations as discussed in the text. The dimensionality is scattering angle in deg. and cross section in b/sr expressed in the laboratory system.

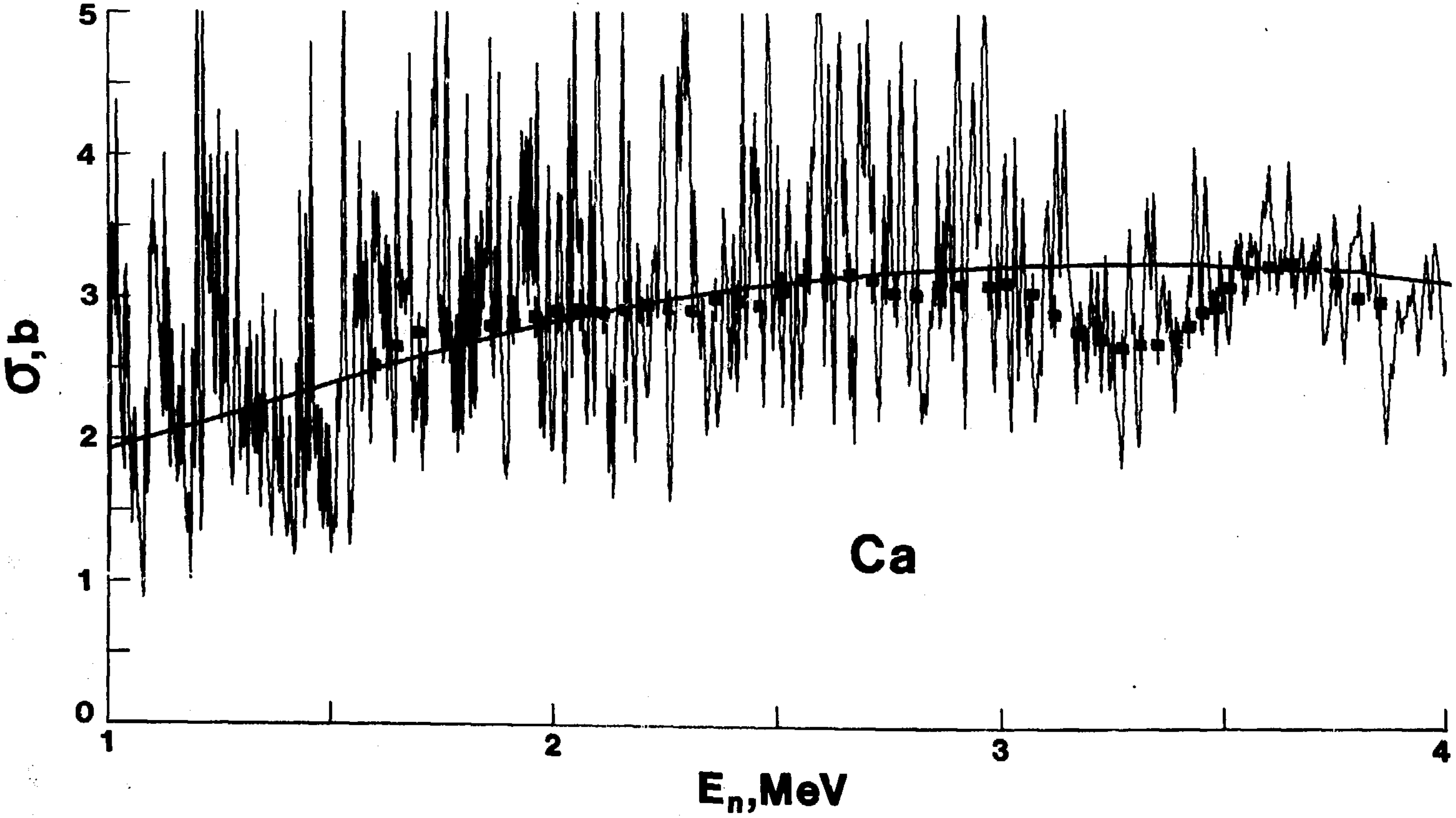

Fig. 3. Angle-integrated elastic-scattering cross sections of calcium. The present experimental results are indicated by ■. The fluctuating curve denotes the evaluated cross sections of Ref. 9. The heavy smooth curve indicates the results of model calculations as discussed in the text.

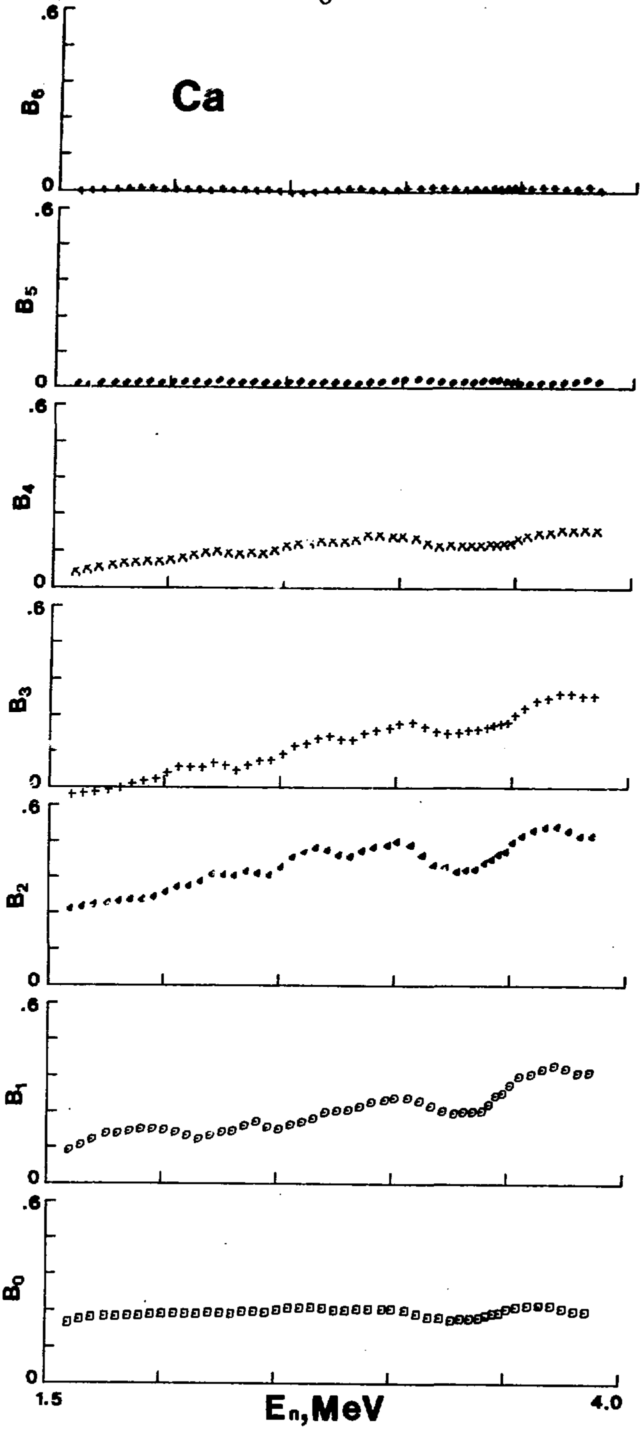

Fig. 4. Calcium B_0 to B_5 coefficients derived from the 250 keV average of the present experimental results. The B-coefficient dimensionality is barns/sr expressed in the center-of-mass system.

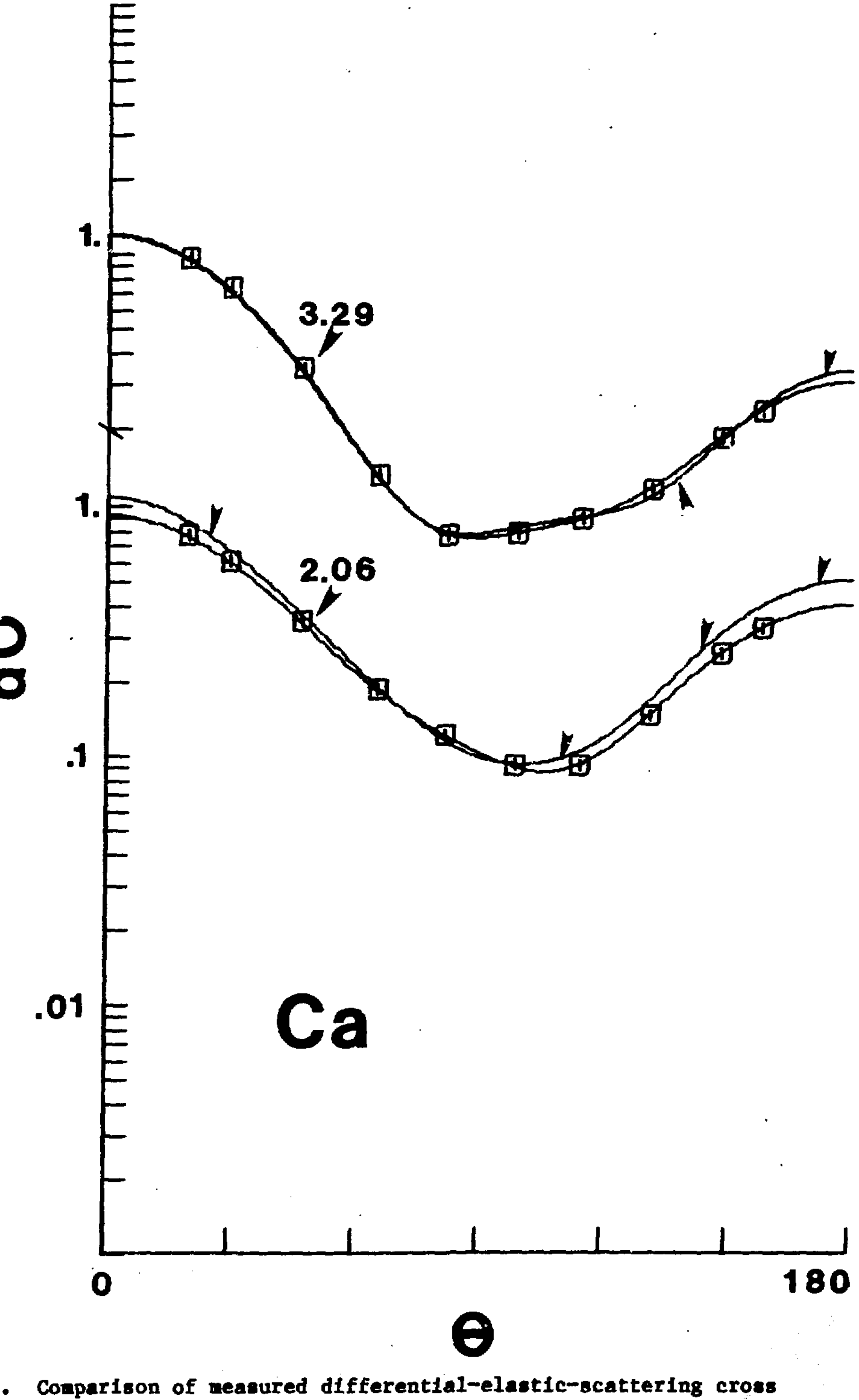

Fig. 5. Comparison of measured differential-elastic-scattering cross sections of calcium at 2.06 MeV (lower) and 3.29 MeV (upper). The present results are denoted by data symbols and the plain curves. Those from Ref. 11 by the curves with "tick" marks. The dimensionality is scattering angle in degrees and cross section in b/sr expressed in the center-of-mass system.

calculations utilized the spherical OM code ABAREX.[14] The OM parameters were deduced by concurrently chi-square fitting all observed differential cross sections over the energy range ≈ 1.5 to 2.6 MeV. The fitting procedure simultaneously adjusted six OM parameters; real and imaginary strengths, radii, and diffusenesses. The energy dependence of the potential was taken from the global parameter set of Ref. 1. That energy dependence is of little note in the present interpretation, but it did provide for a reasonable extrapolation over a much wider energy range. The fitting procedure was pursued in a routine manner and resulted in the parameters of Table 1. Some of these parameters are unusual. The real strength (measured as Vr^2 or in terms of the integral per nucleon, J/A) is larger than conventionally encountered in "global" parameter sets.[1,2,10] The variation can not be attributed to the iso-vector portion of the potential as that term is identically zero. Conversely, the imaginary strength (measured in terms of Wa or J/A) is unusually small. This is not so surprising as it has long been suggested that the imaginary potential is small in the region of shell closure.[3,4] The present interpretation should be sensitive to the imaginary term as the CE component is large throughout the measured energy range.

The potential of Table 1 provides a good description of the present differential and angle-integrated results up to the onset of significant charged-particle emission as illustrated in Figs. 2 and 3. The differences between measurement and calculation are of a magnitude that might easily result from the evident fluctuations even in the illustrated 250 keV averages. Furthermore, the angle-integrated values very nicely extrapolate to low energies and are consistent with very high-energy (e.g., ≈ 10 MeV) measured values where the CE contribution is essentially negligible.[1,11] As the (n;p) and (n;α) cross sections rapidly rise above ≈ 2.6 MeV, the calculated angle-integrated elastic scattering cross sections become consistently larger than the experimentally based quantities (extending to 6 MeV and above). This is to be expected as the decay into the charged-particle channels should significantly dilute the CE component relative to the simple model predictions which did not include charged-particle effects. Comparisons of measured and calculated differential and angle-integrated cross sections in the 3.5 to 4.0 MeV region suggests that the CN decay into the charged-particle channels amounts to 300 to 400 mb. This value is several hundred mb smaller than the cumulative (n;p) and (n;α) cross sections. Concurrently, the calculated neutron total cross section tends to be several hundred mb smaller than the measured values. These observations suggest that a significant portion of the charged-particle cross sections comes from other than CN decay. A direct charge-exchange process provides such an alternate avenue and would qualitatively augment the calculated neutron total cross section while, at the same time, reduce the charged-particle competition with the CE process. Proton and alpha-particle emission at 5.85 MeV has been studied by Foroughi and Rossel.[15] These authors report a dominance of the (n;p) process with more than half of it going through the p_0 and p_1 decay branches (a cumulative cross section of 365 mb). Moreover, the angular distribution of the emitted protons ($p_0 + p_1$) was observed to be very largely in the forward hemisphere in contrast to what one would expect from CN decay.

Significant fractions of the alpha-particle angular distributions were also inconsistent with the CN mechanism. Thus, at energies only somewhat above those of the present measurements, there is experimental evidence for a direct charge-exchange process which is qualitatively consistent with the above noted differences between measured and calculated differential and total cross sections. The apparent situation is unfortunate as calcium, the heaviest naturally-occurring nuclide with an identically zero iso-vector potential, is an attractive anchor point for global OM interpretations. The latter generally do not consider the direct process and, perhaps for that reason, have been troubled in their quantitative representation of high-energy calcium differential-elastic-scattering data. Evidence based upon the present work is indirect and hampered by the fluctuating nature of the cross sections at relatively low energies. However, there would have to be a relatively large deviation of the present experimental results from the true average values to appreciably influence the above conclusions.

The present experimental results improve the definition of elastic-scattering angular distributions relative to those given in ENDF/B-V. It is of interest to assess the effect of this improved definition on shielding applications. For this purpose, a simple infinite-slab Monte-Carlo calculation was carried out. The slab was assumed to consist entirely of calcium and was varied in thickness so as to provide neutron transmissions in the range ≈ 0.01 to 0.9. The penetration through and reflection from the slab of a perpendicularly-incident neutron beam randomly distributed in energy between 1.5 and 4.0 MeV was calculated. Two data bases were employed in the calculation: i) ENDF/B-V, and ii) ENDF/B-V modified to include the additional elastic-scattering detail provided by the present measurements. The penetration and albedo of the slab calculated using the two data bases were very similar (differing by less than 1%) for all trial slab thicknesses. The differences were calculationally significant but negligible with respect to shielding applications, particularly since any practical shield will not be limited to the pure calcium of the idealized test case. Thus, it was concluded that the improved definition of the intermediate-resolution results of the present measurements would very likely have no substantive effect on shielding considerations. This conclusion might be different for much better-resolution data.

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Table 1. Derived Optical-Potential Parameters

Real Potential[a,b]	
V_o = 56.15	MeV
r^c = 1.249	F
a = 0.491	F
$V_o r^2$ = 87.59	MeV • F^2
J/A = 518.11	MeV • F^3
$\langle r^2 \rangle$ = 14.28	F^2
Imaginary Potential[d]	
W_o = 5.709	MeV
r^c = 1.328	F
a = 0.283	F
$W_o a$ = 1.62	MeV • F
J/A = 37.56	MeV • F^3

[a] Woods-Saxon form assuming $V = V_o - 0.3 \times E$ (MeV).

[b] Assuming a spin-orbit term of the Thomas form with a strength of 6.7 MeV.

[c] Assuming $R = r \times A^{1/3}$.

[d] Woods-Saxon derivative form assuming $W = W_o + 0.4 \times E$ (MeV).