Polarization and Differential Cross Sections in the Small-Angle Scattering of Neutrons by Uranium*

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A measurement of the polarization as well as the differential cross section of 0.83-MeV neutrons scattered from uranium through angles of 1.65°, 2.35°, 4.6°, and 10° is described. The observed increase in the differential cross section with decreasing angle is greater (by more than a standard deviation for the three smallest angles) than that expected from nuclear plus Schwinger scattering alone. No corresponding anomalous polarization effects are seen, however. The results of these and previous measurements suggest that this anomalous scattering may be coupled to the fission process. The importance of correcting the measured differential cross sections for finite-solid-angle effects is discussed.

I. INTRODUCTION

THE electromagnetic interaction of a neutron with the Coulomb field of a nucleus can be studied by observing the small-angle scattering of neutrons by heavy nuclei. The differential cross sections of neutrons scattered through small angles (2°–15°) have been measured for several heavy and medium-weight nuclei at a few neutron energies between 0.8 and 4.0 MeV[1] and at 14.2 MeV.[2] Many of these measurements show an increase in the differential cross section as the angle decreases to small values that has not been explained in terms of a "reasonable" interaction between the neutron and the electric field of the scattering nucleus.

In an effort to investigate this anomalous scattering in more detail, we have measured both the polarization and the differential cross section of 0.83-MeV neutrons elastically scattered from uranium through the angles of 1.65°, 2.35°, 4.6°, and 10°. The resulting angular distribution shows an anomalous increase with decreasing angle, similar to that observed previously[1,2] at larger incident-neutron energies. The polarization measurements indicate that this additional scattering is spin independent in the sense that if such scattering is attributed to an additional term in the interaction Hamiltonian, this term contributes nothing (within a rather large experimental uncertainty) to the observed neutron polarization.

Agranovich and Odintsov[3] have shown that the interaction between the magnetic moment of the neutron and the electric field $\mathbf{E}$ of the nucleus (the so-called Schwinger[4] scattering) is the only interaction linear in $\mathbf{E}$ that can be constructed from the vectors $\mathbf{p}$ (linear momentum), $\boldsymbol{\sigma}$ (spin), and $\mathbf{E}$ that describe the system at nonrelativistic energies, and that is not contained as part of the specifically nuclear potential. The observation mentioned above—that any additional terms in the interaction Hamiltonian do not contribute to the polarization—would indicate that such terms are independent of $\boldsymbol{\sigma}$. The simplest term quadratic in $\mathbf{E}$ and independent of $\boldsymbol{\sigma}$ can be identified as the interaction between $\mathbf{E}$ and an induced electric dipole moment of the neutron.

In our analysis of the present measurements, the interaction between the neutron and the scattering nucleus has been taken to be an optical potential (including a spin-orbit term) that describes the nuclear interaction, plus terms that describe the interaction between $\mathbf{E}$ and the magnetic moment of the neutron and between $\mathbf{E}$ and an induced electric dipole moment of the neutron. Both the differential cross section and the polarization of neutrons scattered from this potential were calculated by use of a generalization of the usual Born approximation, proposed recently by Monahan and Elwyn.[5] In Sec. II this method is described briefly as applied to the present calculation, and the results of some general calculations are given. In particular, the dependence of the calculated cross sections and polarizations on the parameters that describe the nuclear optical-model potential is investigated.

Both of the above-mentioned long-range extranuclear interactions lead to additional contributions to the differential cross section at small scattering angles. The magnitude of the contribution from the magnetic-moment interaction, an interaction which can lead to a large negative polarization at small scattering angles,[4] depends on the known value of the magnetic moment of the neutron and thus can be calculated quite accurately. The contribution from the electric-dipole interaction, however, depends on the so-called polarizability of the neutron, a quantity which is not known with any accuracy either experimentally or theoretically.[6]

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[1] Y. A. Aleksandrov, Zh. Eksperim. i Teor. Fiz. 33, 294 (1957) [English transl.: Soviet Phys.—JETP 6, 228 (1958)]; Y. A. Aleksandrov, G. V. Anikin, and A. S. Soldatov, Zh. Eksperim. i Teor. Fiz. 40, 1878 (1961) [English transl.: Soviet Phys.—JETP 13, 1319 (1961)]; Y. A. Aleksandrov and I. I. Bondarenko, Zh. Eksperim. i Teor. Fiz. 31, 726 (1956) [English transl.: Soviet Phys.—JETP 4, 612 (1957)].

[2] Y. V. Dukarevich and A. H. Dyumin, Zh. Eksperim. i Teor. Fiz. 44, 130 (1963) [English transl.: Soviet Phys.—JETP 17, 89 (1963)].

[3] V. M. Agranovich and D. D. Odintsov, in *Transactions of the Second All-Union Conference on Radiation Chemistry, 1960* (AN SSSR Press, Moscow, 1962), pp. 161–165.

[4] J. Schwinger, Phys. Rev. 73, 407 (1948).

[5] J. E. Monahan and A. J. Elwyn, Phys. Rev. 136, B1678 (1964).

[6] V. S. Barashenkov and H. J. Kaiser, Fortschr. Physik 10, 33 (1962). Also see this paper for other references.

The previous measurements[1,2] of the differential cross sections in the small-angle scattering of neutrons by nuclei have been made at about 0.8, 2.0, 2.8, 3–4, and 14.2 MeV. The results of these experiments can be briefly summarized as follows: At $E_n \geqslant 2.0$ MeV, the observed differential cross section at angles $\leqslant 15°$ in the scattering from U, Th, and Pu *but not for other heavy and medium-weight nuclei* is larger than that expected on the basis of nuclear-plus-Schwinger scattering alone. At an energy of about 0.8 MeV, no unusual effects were observed for any nucleus.

In an attempt to interpret his measurements of this enhanced scattering at $E_n \approx 2$ MeV in terms of the neutron polarizability α, Aleksandrov[1] obtained the value $\alpha \approx (8.0 \pm 3.5) \times 10^{-41}$ cm^3; but a more accurate calculation by Fossan and Walt[7] shows that this interpretation of Aleksandrov's results would require $\alpha \geqslant 5 \times 10^{-40}$ cm^3. Both of these values are considerably larger than the estimate $\alpha \leqslant 2 \times 10^{-42}$ cm^3 obtained from various theoretical analyses.[6] Thaler,[8] in his analysis of the low-energy (large-angle) scattering data of Langsdorf *et al.*,[9] deduces an upper limit for the value of α that is an order of magnitude greater than the approximate upper limit obtained theoretically. The small-angle scattering of 0.57-MeV neutrons by U was recently measured by Fossan and Walt.[7] Their results are consistent with an upper limit $\alpha \leqslant 2 \times 10^{-40}$ cm^3 and do not show any anomalous behavior at small angles.

The present small-angle scattering experiment is described in Sec. III. In Sec. IV, these results are discussed in terms of the calculations described in Sec. II, and a possible interpretation of the data is suggested. It is also pointed out in Sec. IV that finite-solid-angle effects become important at small scattering angles. The significance of such corrections for the present measurements is discussed.

It might be mentioned that the polarization of neutrons scattered from heavy nuclei through very small angles had not previously been measured at an energy as low as 0.8 MeV; the expected large negative polarization at small angles has been observed at 3.6 MeV by Gorlov *et al.*[10]

II. CALCULATIONS

It has been shown in Ref. 5 that if one considers the scattering of neutrons from a spherically symmetric potential $V(r)$ that can be written in the form

$$V(r) = V_1(r) + V_2(r), \tag{1}$$

where

$$V_1(r) = 0 \quad \text{for} \quad r \geqslant r_c,$$
$$V_2(r) = 0 \quad \text{for} \quad r < r_c, \tag{2}$$

then the phase shifts describing the scattering from $V(r)$ can be related very simply to those that describe the scattering from the potential $V_1(r)$ alone provided the cutoff radius r_c is chosen large enough that $V_2(r)$ can be treated as a perturbation. These latter phase shifts can be obtained, for example, by a numerical integration of the Schrödinger equation with potential $V_1(r)$ out to the "asymptotic" region $r \geqslant r_c$.

In the present situation we consider the scattering from a potential $V(r)$ of the form (1) where

$$V_1(r) = V_m(r) + V_e(r) + V_p(r) \quad \text{for} \quad r < r_c \tag{3}$$

and

$$V_2(r) = V_e(r) + V_p(r) \quad \text{for} \quad r \geqslant r_c. \tag{4}$$

Here $V_e(r)$ is the potential describing the interaction between the neutron magnetic moment and the nuclear Coulomb field (Schwinger scattering), $V_p(r)$ is that describing the interaction between the induced electric dipole moment and the Coulomb field of the nucleus, and $V_m(r)$ is the nuclear interaction represented by an optical-model potential. The optical-model potential has the form

$$V_m(r) = -Vf(r) - iWg(r) + V_s\left(\frac{\hbar}{m_\pi c}\right)^2 \left(\frac{1}{r}\frac{d}{dr}f(r)\right) \boldsymbol{\sigma} \cdot \mathbf{l}, \tag{5}$$

with

$$f(r) = [1 + \exp((r-R)/a_s)]^{-1},$$

and

$$g(r) = 4\exp((r-R)/a_0)[1 + \exp((r-R)/a_0)]^{-2}.$$

The potentials $V_e(r)$ and $V_p(r)$ are given by

$$V_e(r) = |\mu_n| (e\hbar/2m^2c^2) \boldsymbol{\sigma} \cdot \mathbf{E} \times \mathbf{p}$$
$$= |\mu_n| (Ze^2\hbar^2/2m^2c^2) \phi(r) \boldsymbol{\sigma} \cdot \mathbf{l}, \tag{6}$$

$$V_p(r) = -\tfrac{1}{2}\alpha E^2 = -\tfrac{1}{2}\alpha Z^2 e^2 \psi(r), \tag{7}$$

where μ_n = the neutron magnetic moment, α is the neutron polarizability,

$$\phi(r) = r_s^{-3} \quad \text{for} \quad r \leqslant r_s,$$
$$= r^{-3} \quad \text{for} \quad r > r_s,$$

and

$$\psi(r) = r_s^{-4} \quad \text{for} \quad r \leqslant r_s,$$
$$= r^{-4} \quad \text{for} \quad r > r_s,$$

where r_s is the "charge radius" of the scattering nucleus.

The phase shifts describing the scattering from $V_1(r)$ were obtained with the ABACUS-2 code[11] suitably modified to include the potentials $V_e(r)$ and $V_p(r)$ for $r < r_c$. The polarizations and differential cross sections were calculated with these phase shifts and a specially written computer program based on the formalism described in Ref. 5. The advantage of this method of calculation over the usual Born-approximation methods

[7] D. B. Fossan and M. Walt, Phys. Rev. Letters **12**, 672 (1964); M. Walt and D. B. Fossan, Phys. Rev. **137**, B629 (1965).

[8] R. M. Thaler, Phys. Rev. **114**, 827 (1959).

[9] A. Langsdorf, Jr., R. O. Lane, and J. E. Monahan, Phys. Rev. **107**, 1077 (1957).

[10] G. V. Gorlov, N. S. Lebedeva, and V. M. Morosov, in Proceedings of the Conference on Nuclear Reactions at Low Energies, Moscow, 1958, p. 93 (unpublished).

[11] E. H. Auerbach, Brookhaven National Laboratory Report BNL-6562, 1962 (unpublished).

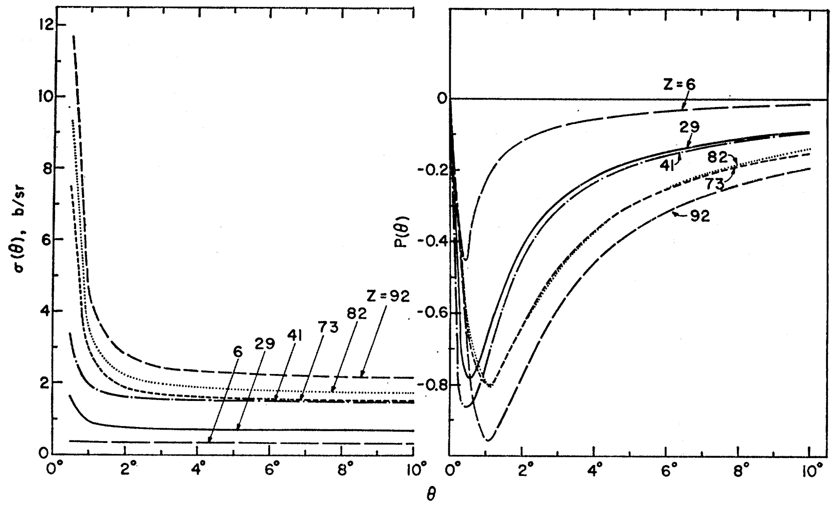

FIG. 1. Calculated differential cross section $\sigma(\theta)$ and polarization $P(\theta)$ for neutrons scattered from various nuclei (with nuclear charge number Z) at 0.8 MeV. The calculations have been corrected for compound elastic scattering, as discussed in the text. The value of α was taken to be 10^{-40} cm^3.

is that all interference terms are taken into account correctly to first order in the perturbation potential $V_2(r)$.

We have calculated several differential cross sections and polarizations in order to show some general features of the scattering at small angles. The curves of $\sigma(\theta)$ for several values of the nuclear charge number Z (Fig. 1) were calculated for the potential described in Eqs. (1)–(7). The parameters of the nuclear optical-model potential are local parameters equivalent to the nonlocal parameters of Perey and Buck[12] (including a spin-orbit potential $V_s=10$ MeV), and both $\sigma(\theta)$ and $P(\theta)$ have been corrected for compound elastic scattering by use of the formalism of Hauser and Feshbach.[13] (In this correction, the reaction cross section predicted by the optical model has been assumed to be equal to the cross section for compound elastic scattering.) As expected, the magnitude of the peak at small angles in both $\sigma(\theta)$ and $P(\theta)$ tends to increase as Z increases. Further, the peak in $P(\theta)$ moves to larger angles as Z increases. The polarizability of the neutron was $\alpha=10^{-40}$ cm^3 in these calculations. This is considerably larger than theoretical estimates[6,14] which give $\alpha \leqslant 2\times10^{-42}$ cm^3. Calculations showing the dependence of $\sigma(\theta)$ and $P(\theta)$ on α and further discussion of this point will be described in the paragraphs that follow.

For a given nucleus of large Z, the small-angle distributions and polarizations change smoothly as a function of incident-neutron energy for energies below 2 MeV when the nuclear interaction is described by an optical model. As the energy increases, the magnitude of the cross section $\sigma(\theta)$ at small θ tends to increase but the shape of the curve $\sigma(\theta)$ versus θ remains the same.

Figure 2 shows the differential cross sections and polarizations for neutrons scattered from U at 0.83 MeV, as calculated for the potentials described in the figure. These calculations were made to determine the contribution (including interference effects) of the separate terms of the potential given by Eqs. (3) and (4). The parameters of the optical-model potential are those suggested by Moore and Auerbach[15] (their set-A parameters) as providing a good fit to differential-cross-section data at angles greater than 20°. In the calculations that include the polarizability interaction, we used $\alpha=10^{-40}$ cm^3. Calculations for a value of α as small as 10^{-42} cm^3 (which, as mentioned above, is thought to be a more reasonable estimate) gave results indistinguishable from the curves marked C in the figure. (The calculation that led to curve C includes the Schwinger and nuclear interactions only.) For the calculations of the differential cross section, curve C is very closely the sum of curve D (nuclear potential only) and curve E (Schwinger interaction only). Thus, the interference between the nuclear and Schwinger scattering amplitudes makes a negligibly small contribution to the differential cross section.

On the polarization curves of Fig. 2, curve C shows the large negative values of polarization expected from the interference between nuclear and electromagnetic scattering amplitudes, and is most closely related to Schwinger's original calculations.[4] Note that the calculation with a nuclear interaction only (curve D) leads to a very small value of polarization at these small angles, even though the depth V_s of the nuclear spin-orbit potential was set equal to 15 MeV in these calculations. Similarly small polarizations are predicted by calculations with a potential that includes the polarizability and nuclear interactions only (curve B). For potentials of the form employed here, the quantity

[12] F. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962).

[13] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[14] L. G. Moroz and V. N. Tretiakov, Doklady Akad. Nauk Belorussk. SSR **8**, 575 (1964).

[15] S. O. Moore and E. H. Auerbach, *Optical Model Analysis of Inelastic Scattering of Neutrons by Heavy Nuclei*, BNL-818(T-317) (Office of Technical Services, Department of Commerce, Washington 25, D. C., 1963). See also, E. H. Auerbach and S. O. Moore, Phys. Rev. **135**, B895 (1964). In the notation of Eq. (5), the set-A parameters are $V=39.8$ MeV, $W=6.9$ MeV, $Vs=15.0$ MeV, $R=8.18\times10^{-13}$, $a_s=0.47\times10^{-13}$ cm, and $a_g=10^{-13}$ cm.

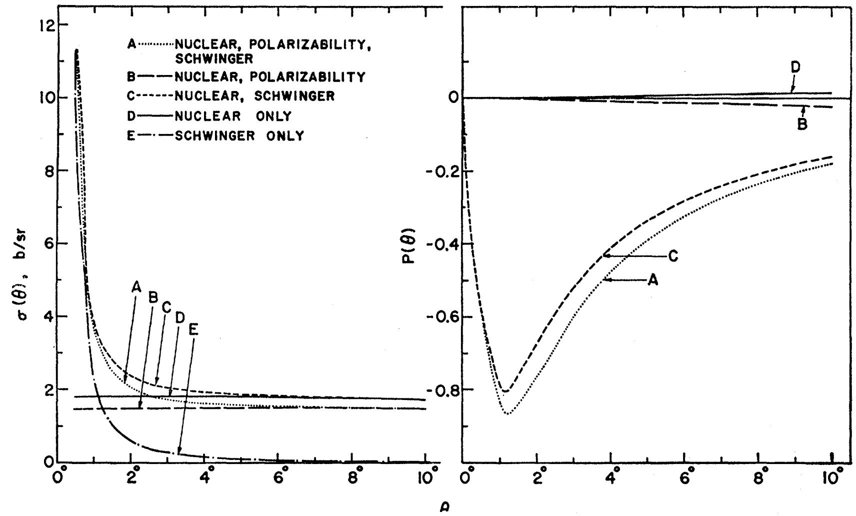

FIG. 2. Calculated differential cross section $\sigma(\theta)$ and polarization $P(\theta)$ for neutrons scattered from uranium at 0.83 MeV for the various terms in the neutron-nucleus interaction potential as shown in the figure. The calculations have been corrected for compound elastic scattering. The parameters of the optical-model potential are those of Ref. 15. The value of α is taken as 10^{-40} cm^3.

$\sigma_p(\theta)=\sigma(\theta)P(\theta)$ is practically independent of α. Therefore the differences between the polarization curves A and C can be attributed to the α dependence of the differential cross section $\sigma(\theta)$. [The polarization $P(\theta)$ is calculated by dividing $\sigma_p(\theta)$ by $\sigma(\theta)$.]

As mentioned, curve B in Fig. 2 is a calculation that includes the polarizability and nuclear interactions only (the Schwinger interaction has been "turned off"). Figure 3 shows similar calculations of the differential cross sections for several values of α. As α increases from $\alpha=0$ to $\alpha=4\times10^{-40}$ cm^3, the absolute magnitudes of the calculated values of $\sigma(\theta)$ decrease. This illustrates that destructive interference occurs between the nuclear and polarizability scattering amplitudes. Such an effect has been pointed out by Weisskopf and Feshbach,[16] and described in more detail by Fossan and Walt.[7] It can be noted, furthermore, that the slopes of the differential-cross-section curves at angles $\theta\leqslant10°$ do not change appreciably in the range $0\leqslant\alpha\leqslant4\times10^{-40}$ cm^3. It is only for $\alpha\geqslant4\times10^{-40}$ cm^3 that the slopes of the curves change appreciably as a function of α.

The absolute value of the differential cross section at angles down to about 3° is determined largely by the nuclear scattering. With an optical-model description of the nuclear interactions, it is often possible to fit angular-distribution measurements with more than one set of parameters. For example, Moore and Auerbach[15] present two sets of optical-model parameters that lead to good fits to measured differential cross sections for U at $\theta\geqslant20°$. For $E_n=0.83$ MeV, $\theta\leqslant10°$, and a given value of α, the differential cross sections and polarizations calculated with this second set of parameters (set B of Ref. 15) have the same shapes as those obtained with the set-A parameters but the absolute magnitudes are different. Further, in a series of calculations at small angles ($\theta\leqslant10°$) with $\alpha\leqslant10^{-40}$ cm^3 we found that varying several of the parameters of the optical-model potential (individually or together) changed the absolute magnitude but not the shapes of the curves of the resultant cross sections and polarization. From these and previous calculations, it is clear that in cases in which the nuclear interaction can be represented by an optical-model potential, measurements of the differential cross section and polarization in small-angle scattering can determine only a large upper limit for the value of the polarizability of the neutron—unless it should turn out that $\alpha>4\times10^{-40}$ cm^3.

[16] V. F. Weisskopf and H. Feshbach (private communication to R. M. Thaler, Ref. 7).

III. EXPERIMENT

The present experimental arrangement, which is similar to that of Fossan and Walt,[7] is shown in Fig. 4 in schematic form. Protons accelerated by the Argonne 4.5-MeV Van de Graaff generator were incident on rotating evaporated-lithium-metal targets (about 50–80-keV thick to 1.9-MeV protons) placed at the

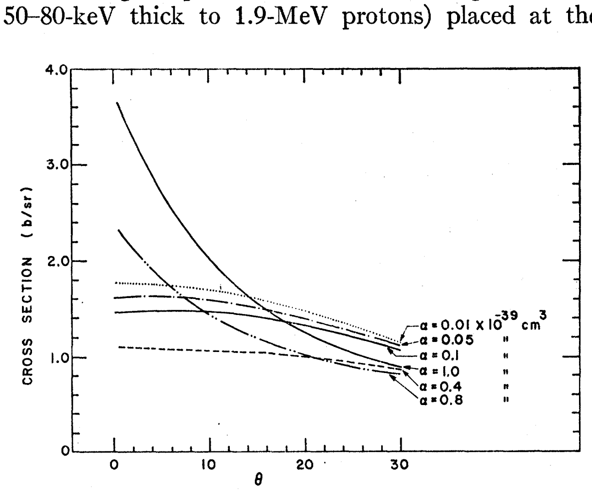

FIG. 3. Differential cross sections for 0.83-MeV neutrons scattered from uranium. The potential used in these calculations includes the nuclear and polarizability interactions *only*, for various values of α. The parameters of the optical-model potential are those of Ref. 15.

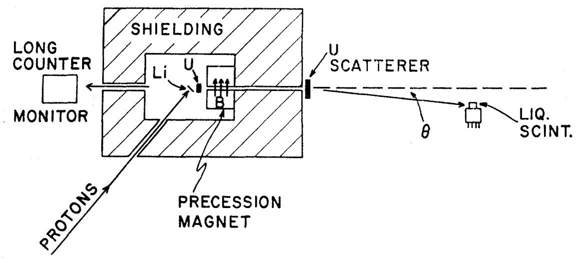

FIG. 4. Schematic diagram of the experimental arrangement. The sample (marked U) shown between the lithium target and the precession magnet is called the filter sample in the text. It is in place as shown only for background measurements when the uranium scatterer is removed.

center of a shielded source tank. (This source tank has been used in previous experiments.[17]) Neutrons produced at 51° relative to the incident proton beam in the $Li^7(p,n)Be^7$ reaction passed between the poles of an electromagnet and through a tapered rectangular collimator which was fabricated from linen-base bakelite and inserted into the larger collimator opening in the previously designed source tank. The collimator channel flared from a minimum cross section of $\frac{3}{16}\times\frac{3}{16}$ in. at its small end (placed about 5 in. from the lithium target) to a maximum of $\frac{1}{2}\times\frac{1}{2}$ in. at the large end (about 33 in. from the source spot).

After passing through the collimator, the neutrons impinged on a cylindrical uranium scatterer $\frac{1}{2}$in. thick, oriented with the axis of the cylinder parallel to the beam direction; all neutrons leaving the collimator were intercepted by the scatterer. Scattered neutrons were detected by a liquid scintillator enclosed in a glass container in the form of a cylinder $2\frac{1}{8}$ in. in diameter and $1\frac{1}{2}$ in. high with its flat face cemented to an RCA 6810A photomultiplier tube.[18] The scintillator was placed about 60 in. from the center of the scatterer. The axis of the phototube was perpendicular to the beam direction, and the entire detection unit moved on a track parallel to the tube axis. In this way the scintillator could be set at any scattering angle and into the direct beam with relative ease. Differential cross sections and polarizations were measured at four angles—1.65°, 2.35°, 4.6°, and 10°.

The liquid scintillation detector was used as a biased proton-recoil counter with the bias set for effective exclusion of those neutrons with energy less than ~0.45 MeV. A space-charge-limiting technique, which made use of the difference between the pulse shapes of scintillator events induced by electrons and photons, was utilized to discriminate almost completely against γ rays.

A BF_3 long counter served as a neutron monitor. It was placed to detect neutrons that emerged through a small opening in the shield tank into a backward angle relative to the direction of the proton beam. Throughout the experiment the number of neutrons counted per run was normalized to this monitor counting rate.

The effectiveness of the geometrical shielding of the collimator at the detector distance of 60 in. was evaluated by measuring the relative counting rates in the liquid scintillator as it was moved across the direct neutron-beam position with no scatterer in place. The resulting beam profile is shown in Fig. 5. In the present experiment the smallest scattering angle was 1.65°. This angle corresponds to a distance of 4.5 cm from the center of the direct neutron beam. With no scatterer in place, the ratio of the counting rate with the detector in this position to the rate with the detector in the direct beam (at zero in Fig. 5) is about 1 to 2000.

A major source of the neutron background encountered in the present measurements is the scattering of neutrons from the air between the collimator exit and the detector. It was possible, at least at scattering angles $\geqslant 2°$, to reduce this background by placing a sheet of Lucite (24 in. long, 6 in. high, and 1 in. thick) between the scintillation detector and the direct beam of neutrons passing through the collimator. With the detector set to count scattered neutrons, the counting rates for the most adverse conditions (at 1.65°) were about 33 counts/min with the uranium scatterer in place and 16 counts/min with the scatterer removed.

Because of the large air-scattering background and also because of the possibility of an appreciable background contribution due to neutron scattering from the walls of the collimator, a simple determination of the counting rate with the scatterer removed does not give a true measure of the background effects. In order to approximate a true background measurement, the scattering sample was removed and a second uranium sample (to be called the "filter" sample in the paragraphs below) that had the same transmission as the scatterer (~0.62) was inserted between the neutron source and the entrance to the collimator. In this arrangement, the neutron-flux incident on the air column between the collimator exit and the detector was subject to about the same attenuation as when the filter was removed and the scatterer put into place. Also, to first order, the arrangement correctly accounts for the effects of scattering from the collimator walls

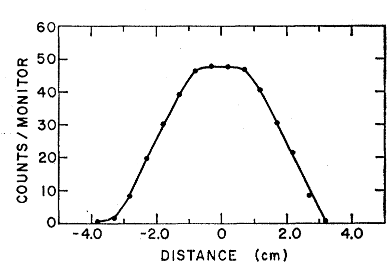

FIG. 5. Profile of the collimated neutron beam at the detector position 60 in. from the collimator exit, measured with the same detector as was used for the scattering measurements.

[17] See, for example, A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr., Phys. Rev. 128, 779 (1962) and other references listed therein.

[18] We wish to thank Dr. A. B. Smith for the loan of his liquid scintillation detector and associated electronic equipment.

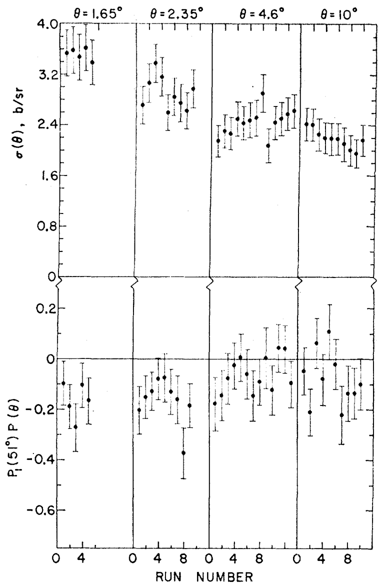

FIG. 6. Uncorrected differential cross sections $\sigma(\theta)$ and polarization products $P_1(51°)P(\theta)$ as a function of run number for each scattering angle θ. Each run corresponds to a sequence of operations as described in the text.

into the detector. All background measurements were made with the filter sample inserted as described above.

The polarization of neutrons scattered through a given angle θ was measured by determining the number of neutrons scattered into the detector at the angle θ, first with the electromagnet off and then with it turned on such that its magnetic field was sufficient to precess the neutron spins by 180°. These measurements can be related to the product $P_1(51°)P(\theta)$, where $P_1(51°)$ is the polarization of the neutrons emitted at 51° in the $Li^7(p,n)Be^7$ reaction, and $P(\theta)$ is the polarization that would arise if unpolarized neutrons incident on the scatterer were scattered through the angle θ. The polarizations $P(\theta)$ were obtained from the measured products by use of previously determined values of $P_1(51°)$.[19]

The sums of the magnet-on and magnet-off measurements are proportional to the (unpolarized) differential cross sections. The normal sequence of measurements at each scattering angle was (1) scatterer in place, filter sample out, magnet on; (2) scatterer in place, filter sample out, magnet off; (3) scatterer out, filter sample in place, magnet on; and (4) scatterer out, filter sample in place, magnet off. This sequence was repeated at least five times (usually more) at each scattering angle.

Figure 6 shows the values of the differential cross sections (not corrected for any of the effects to be discussed below) and the polarization products $P_1(51°)$ $P(\theta)$ as a function of run number. The errors shown are based on the statistical accuracy as well as on estimates of the uncertainties associated with the geometrical measurements, etc. The scatter of the points in Fig. 6 is no larger than that expected statistically on the basis of the indicated errors. Thus there is no evidence of any significant change in experimental conditions between runs. Throughout this experiment, an effort was made to keep the Van de Graaff beam as steady as possible.

Absolute values of the differential cross sections were obtained from the total number of neutrons detected at a given scattering angle relative to the number incident on the scatterer. This latter number was determined by placing the detector into the direct neutron beam and opening up the collimator so that the beam covered the entire area of the scintillator. A measurement in the direct beam was made once during each sequence of runs described above. The ratio of the counts in the scattered beam to those in the direct beam is proportional to the differential cross section, the constant of proportionality being simply evaluated from the geometrical characteristics of the experimental setup.

The cross sections thus obtained were corrected for the presence of inelastic scattering by use of the known energy sensitivity of the detector and previously measured inelastic differential cross sections[20] extrapolated to these small scattering angles. The cross sections were also corrected for multiple scattering by use of previously developed computer codes.[21] The values of the cross section thus obtained are given in column (2) of Table I. The polarization data were not corrected for these effects; but approximate calculations indicate that the corrected values lie well within the rather large experimental errors associated with these points. Other effects such as the differing detector efficiency for neutrons incident at different angles, the counting-rate dependence of the detector, and any further effects not specifically known were accounted for by normalizing all measured differential cross sections to the known cross section of a standard scatterer; in this case the standard chosen was polyethylene (CH_2). Measurements similar to those described above for uranium were performed for CH_2 scatterers at angles near 2°. Multiple-scattering corrections were made by use of the known hydrogen and carbon differential cross sections extrapolated to the small-angle region. These corrections took account of the energy dependence of the multiply scattered neutrons. The corrected CH_2 results normalized to the corresponding theoretically expected cross sections[22] were utilized to obtain final absolute differential cross sections for uranium. These are shown in column 3 of Table I. It should be noted that this normalization procedure affects only the final absolute values for uranium—not the relative cross sections at different values of the scattering angle. The polarization of neutrons scattered from CH_2 was found to be zero within the experimental uncertainty. A

[19] A. J. Elwyn and R. O. Lane, Nucl. Phys. 31, 78 (1962).

[20] A. B. Smith, Nucl. Phys. 47, 633 (1963).

[21] R. O. Lane and W. F. Miller, Nucl. Instr. Methods 16, 1 (1962).

[22] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, BNL-325 and Supplement (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955 and 1957).

TABLE I. Measured values of the differential cross section and polarization for 0.83-MeV neutrons scattered from uranium. In column 2 are shown the corrected absolute values of the elastic cross sections obtained from the ratio of counts in the scattered beam to those in the direct beam. Column 3 gives the measured values normalized to the CH_2 standard scatterer. Column 4 shows the total scattering cross sections obtained in the supplementary experiment discussed in the text. In column 5, a few of the values in column 4 have been corrected for inelastic scattering. The errors shown for $\sigma(\theta)$ at $\theta \geqslant 23°$ are based on an assumed 5% error in the total cross sections for the carbon scatterer that was used as a standard in the supplementary experiment. At $\theta \leqslant 15°$, the errors shown (columns 4 and 5) have been increased (somewhat arbitrarily) to about 8% to account for additional experimental uncertainties. Column 6 gives the values of the polarization obtained in the experiment with the scintillation detector. Column 7 shows polarization values obtained in the supplementary experiment. For all values of θ, the errors shown in columns 6 and 7 are based mainly on counting statistics.

1	2	3	4	5	6	7
		$\sigma(\theta)$ (b/sr)			$P(\theta)$	
θ (deg)	Absolute (from counts)	Normalized to CH_2	BF_3 counter results	Corrected for inelastic events	Scintillation counter results	BF_3 counter results
1.65	3.91±0.25	3.36±0.21			−0.59±0.13	
2.35	3.17±0.19	2.73±0.16			−0.56±0.12	
4.6	2.64±0.16	2.27±0.13			−0.25±0.09	
10.0	2.25±0.14	1.94±0.12	1.92 ±0.15	1.78 ±0.14	−0.28±0.12	−0.09 ±0.02
15.0			1.78 ±0.14	1.64 ±0.15		−0.063±0.010
23.0			1.576±0.097	1.431±0.079		−0.027±0.009
44.0			0.942±0.047			0.028±0.011
64.0			0.537±0.027			0.078±0.012
86.0			0.419±0.021			0.056±0.019
100.0			0.391±0.020			0.034±0.011
106.0			0.400±0.020			0.016±0.013
128.0			0.359±0.018			−0.004±0.019
149.0			0.334±0.017			0.001±0.016

polarization close to zero is expected in scattering from CH_2 at these small angles and this result served as a check on the other polarization measurements.

The final results for the differential cross sections and polarizations for neutrons scattered from U at 0.83 MeV are shown in Table I. Also shown in the table (columns 4, 5, and 7) are the results of a supplementary experiment in which previously described techniques[17] were employed to measure $\sigma(\theta)$ and $P(\theta)$ at angles between 10° and 149°. All of these data, taken with detectors consisting of banks of BF_3 counters in oil moderator enclosed in shielded tanks, were corrected for the effects of the second group of neutrons (leaving Be^7 in an excited state at 0.43 MeV) and for multiple scattering. The large-angle results are in good agreement with previous measurements.[23] Although the listed values (Table I) of the differential cross sections at 10° differ among themselves by about 8%, they agree within the stated accuracy; the value of $P(\theta)$ at $\theta = 10°$ is somewhat higher in the experiment utilizing the scintillation detector, but the statistical uncertainty in the measurement is rather large. As mentioned previously, the relative values of $\sigma(\theta)$ at different values of θ for a given normalization are believed to be much more accurately determined than the absolute values of $\sigma(\theta)$. The errors shown in the table are based mainly on counting statistics but also include estimates of various other uncertainties.

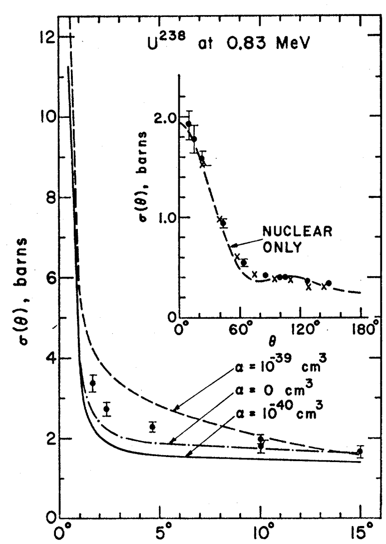

FIG. 7. Differential cross sections for 0.83-MeV neutrons scattered from uranium. The experimental values (solid points) are from columns (3) and (4) of Table I; the calculations are based on the potential in Eqs. (3)–(7) for various values of α. The inset compares the measurements for angles $\theta \geqslant 10°$ (column 4, Table I) with previous measurements (Ref. 23) and with calculations based only on the optical-model potential of Eq. (5). The parameters of the optical-model potential are those of Ref. 15.

IV. RESULTS AND DISCUSSION

The results presented in Table I are compared with calculations (discussed in Sec. II) in Figs. 7 and 8. In these figures the nuclear potential was taken to be the optical-model potential of Eq. (5). The parameters of the model are the set-A values given by Moore and Auerbach.[15] The small-angle ($\theta \leqslant 15°$) calculations are presented for three values of α in an attempt to ascertain the accuracy to which it is possible to determine a value of the polarizability from the measurements. The insets (in Figs. 7 and 8) compare the large-angle data (closed

[23] R. O. Lane, A. Langsdorf, Jr., J. E. Monahan, and A. J. Elwyn, Ann. Phys. (N. Y.) 12, 135 (1961).

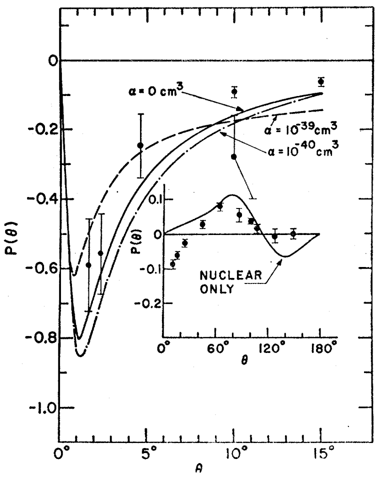

FIG. 8. Polarizations of 0.83-MeV neutrons scattered from uranium. The experimental values (solid points) are from columns (5) and (6) in Table I; the calculations are based on the potential in Eqs. (3)–(7) for various values of α. The inset compares the measurements at angles $\theta \geqslant 10°$ (column 6, Table I) with calculations based only on the optical-model potential of Eq. (5). The parameters of the optical-model potential are those of Ref. 15.

circles and x's) with calculations based on the nuclear optical-model potential alone.

If it is assumed that the interaction between the neutron and the nucleus can be described by a potential with terms representing the nuclear, polarizability, and Schwinger interactions only, then the results shown at $\theta < 10°$ in Figs. 7 and 8 are not inconsistent with a value of α somewhat greater than 10^{-40} cm^3. This is a larger value than is believed to be reasonable. As can be seen by comparing the observed polarization with the curve for $\alpha = 0$ in Fig. 8, the large negative polarizations for $\theta < 10°$ can be explained on the basis of nuclear and electromagnetic interactions alone. In fact, because of the large errors, the polarization data are not inconsistent with the calculations for $\alpha = 0$ or $\alpha = 10^{-39}$ cm^3, at least for angles $\theta < 10°$.

As pointed out in Sec. II, the absolute value of the calculated differential cross section is determined in large part by the nuclear interaction. Because of the ambiguity associated with the nuclear potential, it is useful to consider only the slope of the cross-section curves at small angles in any assessment of anomalous small-angle scattering. In Fig. 9 we plot only the "polarizability cross sections" (calculations performed with nuclear and polarizability interactions only) for neutron polarizabilities $\alpha \leqslant 4 \times 10^{-40}$ cm^3 and $\alpha = 8 \times 10^{-40}$ cm^3. As was pointed out earlier in reference to Fig. 3, the slope for $\theta < 10°$ does not change appreciably for polarizabilities in the range $0 \leqslant \alpha \leqslant 4 \times 10^{-40}$ cm^3. Figure 9 compares the calculated curves with the measured cross sections (open circles) from which the contribution of the Schwinger scattering (corrected for solid-angle effects) has been subtracted. (The points shown as the x's will be discussed below.) As an aid in comparing the slopes of the curves of cross section as a function of angle, the results obtained with the scintillator detector (column 3 of Table I) and those obtained with the shielded BF_3 counters (column 5) have been normalized to the values at 10°, the point of overlap of the two experiments. Further, both calculated curves were normalized to the measured value at $\theta = 15°$. It is clear that the data represented by the open circles fall on a curve whose slope is more nearly consistent with a value of the polarizability between 4×10^{-40} cm^3 and 8×10^{-40} cm^3 than with values $\alpha \leqslant 4 \times 10^{-40}$ cm^3.

The effects of the spatial extension of the scatterer and the detector are increasingly important as the scattering angle becomes smaller. The differential cross section for Schwinger scattering evaluated at 1.65°, 2.35°, and 4.6° (the nominal angles at which the present measurements were made), are, respectively 0.90, 0.45, and 0.113 b/sr. The corresponding Schwinger cross sections averaged over the surfaces of the scatterer and detector[24] used in these measurements are 1.08, 0.47, and 0.115 b/sr at these same nominal angles. Arguments for the existence of anomalous small-angle neutron scattering are based on the slope of the curve depicting the difference between the measured differential cross section and the differential cross section for Schwinger scattering. Obviously these solid-angle corrections can cause substantial changes in this slope and therefore can be critical in such arguments. The properly averaged Schwinger cross sections have been subtracted to obtain the points shown in Fig. 9.

These solid-angle corrections seem not to have been considered in previous measurements of small-angle neutron scattering. The experimental arrangement that

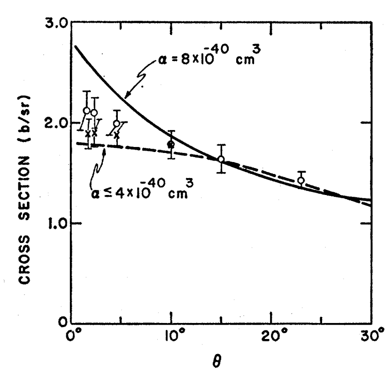

FIG. 9. Differential cross sections for 0.83-MeV neutrons scattered from uranium. The curves were calculated for a potential that includes only the nuclear and polarizability interactions; the smooth curves calculated for $\alpha \leqslant 4.0 \times 10^{-40}$ cm^3 and $\alpha = 8.0 \times 10^{-40}$ cm^3 have been normalized at $\theta = 15°$. The contributions (corrected for solid angle effects) due to the Schwinger scattering terms have been subtracted from the measurements, the open circles being the values listed in columns (3) and (4) of Table I while the x's are the results of a second experiment performed with scintillators (as described in Sec. IV).

[24] J. E. Monahan and A. J. Elwyn, Nucl. Instr. Methods 14, 348 (1962); Argonne National Laboratory Report ANL-6420, 1961 (unpublished). The numerical evaluation of the four-dimensional integrations involved in these calculations is described in these references.

was used by Fossan and Walt[7] is similar in spatial extent to the present setup. Therefore we can estimate the magnitude of this correction for their measurements. For angles $\geqslant 3°$ (the smallest angle at which the differential cross section was determined by Fossan and Walt) these corrections are not important. We have not been able to make a similar estimate in the case of Aleksandrov *et al.*[1]

If the finite-solid-angle corrections are similar to those calculated for our experimental arrangement, then the cross sections measured by Aleksandrov *et al.* for 0.8-MeV neutrons scattered from uranium at $\theta \geqslant 3°$ can be compared with the present results. The absolute values of the differential cross sections obtained by them are about 25–30% larger than our values at 0.83 MeV. Also, the slope of the data points is closer to zero in their work than in the present measurements. As will be discussed later, the differences in average energy and energy resolution between the two experiments may be important in explaining these discrepancies.

The points indicated by the x's in Fig. 9 are the results of a second experiment. The procedure with a few modifications is the same as the experimental method (described in Sec. III) that was used to obtain the results discussed above. At 4.6°, 2.35°, and 1.65°, although the two experiments agree within the indicated uncertainty, the second measurements (the x's) are systematically lower than the previous ones (open circles). Furthermore, the slope corresponding to the general trend of the open circles is somewhat steeper than that for the x's. In fact, the angular distribution obtained in the second measurement is not in disagreement with $\alpha \leqslant 4\times10^{-40}$ cm^3.

The experimental conditions encountered during the second set of runs which much poorer than during the original measurement. The instabilities of both the Van de Graaff generator and the detector electronics led to much larger fluctuations in the data points from run to run than had been observed in the first experiment (Fig. 6, Sec. III). Possibly more important is the fact that the energy spread associated with the incident neutron beam during the second set of measurements was twice that of the first set. Thus if the differential cross section at any angle has a strong energy dependence, the increased instability would lessen the expected reproducibility from run to run, and the larger energy spread would give a different apparent cross section.

Both sets of data have been shown on Fig. 9 for completeness, and to point out some of the difficulties encountered in experiments of this type. From a reasonably thorough analysis of the data and a knowledge of the experimental conditions, we feel that the original data [open circles in Fig. 9 and the results in Table I] are the more reliable.

The present results, therefore, suggest a value of the neutron polarizability between 4 and 8×10^{-40} cm^3 *provided* that the interaction between the neutron and the uranium nucleus is assumed to be described by a potential of the form of Eqs. (3) and (4), containing terms representing nuclear, electromagnetic, and polarizability interactions *only*. It seems clear from the data at hand, however, that the interaction is not this simple. In a small-angle measurement of 0.57-MeV neutrons scattered from uranium, Fossan and Walt[7] did not observe the so-called "anomalous scattering" (the nonzero slope in Fig. 9) that we observe at 0.83 MeV. These authors also analyze their measurements in terms of the polarizability, nuclear, and electromagnetic interactions. They conclude that $\alpha \leqslant 2\times10^{-40}$ cm^3 and therefore that the "anomalous scattering" observed at higher energies could not be explained in terms of the polarizability of the neutron. The fact that in the previous experiments[1,2] this small-angle anomaly is observed in the scattering of neutrons from only a *few* high-Z nuclei and, even for these nuclei, only at energies greater than 1 MeV, is further confirmation of this conclusion. It appears, therefore, that another explanation must be found for the present results and also for the results of the previous experiments. Barashenkov and Kaiser[6] have summarized the unsuccessful attempts to explain the results of the previous work.

With reference to the earlier work, Dukarevich and Dyumin[14] observe that an anomalous contribution to the differential cross section has been established only in the scattering of neutrons from U, Th, and Pu, and that the magnitude of the anomaly increases with increasing neutron energy. They further note that no anomalous increase in scattering at small angles was observed in the scattering of 14.2-MeV neutrons from the (deformed) nucleus W. Dukarevich and Dyumin then suggest the possibility that the effect is associated with specific features of fissionable nuclei.[25] The present results are consistent with this suggestion and further, when compared with the negative results of Fossan and Walt, indicate the possibility that the effect is coupled with the fission process itself. The fission threshold for U^{238} occurs at a neutron energy of approximately 0.6 MeV. The present measurements were carried out at an energy a little above this threshold, while these of Fossan and Walt were made at energies slightly below this threshold.

[25] In a contribution to the International Conference on the Study of Nuclear Structure with Neutrons, held in Antwerp, Belgium, 1965, Anikin, Aleksandrov, and Soldatov report further measurements of the small-angle differential cross sections for neutrons scattered from the fissionable nucleus U and from the nonfissionable nuclei Pb and Cu at energies between 0.57 and 8.4 MeV. The data for U seem to indicate deviations from the cross sections calculated by use of a combined optical-model and Schwinger interaction for $\theta \leqslant 8°$ at energies greater than 1 MeV. The data for Cu show no such deviation. And although the measurements on Pb do deviate, both the report of Anikin *et al.* and further calculations indicate that the deviations are smaller and vary less systematically with energy than in the case of U. As mentioned earlier in the present report, a failure to correct for the effects of finite solid angle (particularly at the smallest angles) could account for some of the deviations observed; it is not clear whether or not such corrections were made in the work of Anikin *et al.*

This possibility may also explain the lack of complete reproducibility noted above in our second measurements of the cross section at 1.65°. The two sets of present results differed considerably in the energy spread in the incident neutron beam. In the measurements with the larger energy spread (the x's in Fig. 9), the incident neutron beam contained a larger fraction of low-energy neutrons. If the anomalous scattering is coupled to the fission process, it is reasonable to expect that the strong energy dependence of the fission cross section of U^{238} in the energy region of the present measurements would be reflected in a strong energy dependence of the anomalous scattering in this same region. Thus, in the region in which the anomalous component of the cross section is *small*, measurements carried out with a beam containing a larger fraction of low-energy neutrons would give an apparent average cross section that is lower than the average that would be obtained from measurements performed with neutron beams that are defined more precisely in energy. Since the differential cross section at the smallest angle contains a larger contribution of "anomalous events," it would be expected to be more sensitive to such differences in beam-energy spread and also to any instabilities in the control of the mean energy of the neutron beam. The fact that the earlier measurements[1] for 0.8-MeV neutrons scattered from U did not show the small-angle anomaly may also be due to the difference between the beam-energy spread in their experiment and that in the present work although it is not clear that the energy distribution of the incident beam used in the earlier work would decrease their measured small-angle results as it must to be consistent with the interpretation of the anomalous scattering described above.

Since the "anomalous contribution" to the cross section occurs only at very small angles, the contributing interaction is probably of a long-range nature. On the assumption that $\alpha \leqslant 10^{-41}$ cm^3, we have calculated the differential cross section $\sigma(\theta)$ and the cross section $\sigma_p(\theta)=\sigma(\theta)P(\theta)$ for the potential described in Eqs. (3)–(7). The optical-model parameters are the set-A parameters referred to previously.[15] The differences between the present measurements (shown in Table I, columns 3 and 6) and the corresponding calculated values are plotted as a function of angle in Fig. 10. The effects of the spatial extension of the scatterer and detector have been taken into account for the points shown in Fig. 10. From this figure it is clear that, within the accuracy of the measurements, the interaction that produces the "anomalous" scattering does not contribute to the polarization of the scattered neutrons. This conclusion is almost independent of the value of α. Even though of limited accuracy, this result provides an additional condition that must be satisfied by any phenomenological potential proposed to explain the "anomalous" small-angle scattering.

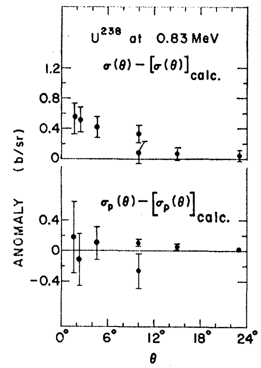

FIG. 10. The difference between measured differential cross sections $\sigma(\theta)$ and polarized cross sections $\sigma_p(\theta)=\sigma(\theta)P(\theta)$ and calculations of these quantities based on the potential of Eqs. (3)–(7) for a value $\alpha=10^{-41}$ cm^3 at angles $\theta\leqslant 23°$.

For example, Redmond[26] has shown that a sufficiently strong spin-orbit force localized at the nuclear surface can give rise to enhanced small-angle scattering. He further suggests that this result might be important in explaining the observed anomalous small-angle scattering of neutrons. Although this suggestion deserves further investigation, it seems unlikely that any reasonable spin-dependent interaction (e.g., one that decreases as an inverse power of r) could give predictions consistent with the present polarization data.

Because of the scarcity of experimental information, this discussion is necessarily tentative. Further experimental study of the detailed energy dependence of the small-angle scattering of neutrons from fissionable (and nonfissionable) nuclei—particularly in energy intervals just below and just above the fission threshold—may prove useful in determining the nature of this anomalous scattering.

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[26] R. F. Redmond, International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, Belgium, July, 1965 (unpublished).