for their invaluable contributions to the experimental setup and run, even while simultaneously doing measurements of their own in the polarized beam. Thanks are also due to Charles Chiu for his help during the experimental run, and to Mrs. Barbara Levine for her assistance with the optical-model fitting program.

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Small-Angle Elastic Scattering of Fast Neutrons and the Electric Polarizability of the Neutron*

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The differential cross section for elastic scattering of 0.57-MeV neutrons by uranium was measured at seven angles between 3.6° and 18° to a relative accuracy of about 4%. After subtraction of the Schwinger scattering contribution, the data show no evidence of enhanced small-angle scattering such as that previously observed at higher energies by Aleksandrov and by Dukarevich and Dyumin. The present data are consistent with an electric polarizability α of the neutron of less than 2×10^{-40} cm^3. As this upper limit to α is smaller than the value needed to account for the anomalous small-angle scattering reported by Aleksandrov and by Dukarevich and Dyumin, it is concluded that the enhanced scattering is not produced by an electric polarizability of the neutron.

I. INTRODUCTION

MEASUREMENTS of the elastic scattering of fast neutrons by heavy nuclei have shown that the differential cross section for scattering at angles below about 15° exhibits an unexpected increase with decreasing scattering angle. Aleksandrov[1] observed such an increase for Pu and U at an average energy of about 2 MeV, and Aleksandrov, Anakin, and Soldatov[2] detected a similar effect in U and Th at about 2.8 MeV. No such effect was seen in the other elements studied. Dukarevich and Dyumin,[3] using monoenergetic 14.2-MeV neutrons, detected a similar enhancement in the scattering cross sections of Pu and Th at small angles. However, Aleksandrov *et al.*[2] did not observe the effect at an average energy of 0.8 MeV nor did Aleksandrov and Bondarenko[4] who made measurements of Pb and Cu at an average neutron energy of 3 to 4 MeV.

Because of the angular dependence, the observed small-angle effect was not attributed to either nuclear or Schwinger[5] scattering. The nuclear contribution to the differential cross section at small angles is a slowly varying function of angle, while the Schwinger scattering, which results from the interaction of the neutron magnetic moment with the nuclear Coulomb field, is confined to angles below about 2°.

It has been suggested by Aleksandrov and Bondarenko[4] that increased small-angle scattering might be produced by the interaction of the nuclear Coulomb field E with an induced electric dipole moment, $\mathbf{p}=\alpha\mathbf{E}$, of the neutron. This interaction, whose Hamiltonian is given by $H=-\frac{1}{2}\alpha E^2$, could produce an increase in $\sigma(\theta)$ for angles less than about 15°, the magnitude of the increase being dependent on the electric polarizability α of the neutron. From the experimental data at 2 MeV Aleksandrov[1] obtained the value $\alpha=(8\pm3.5)\times10^{-41}$ cm^3. However, an analysis by Thaler[6] of low-energy neutron-scattering data taken by Langsdorf, Lane, and Monahan[7] led to an upper limit of $\alpha=2\times10^{-41}$ cm^3. Furthermore, values of α obtained from meson theory,[6,8] from the cross section for photoproduction of pions,[9] and from scattering of photons by deuterons[10] are at least an order of magnitude smaller than the value

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[1] Y. A. Aleksandrov, Zh. Eksperim. i Teor. Fiz. **33**, 294 (1957) [English transl.: Soviet Phys.—JETP **6**, 228 (1958)].

[2] 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)].

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

[4] Y. A. Aleksandrov and I. I. Bondarenko, Zh. Eksperim. i Teor. Fiz. **31**, 726 (1956) [English transl.: Soviet Phys.—JETP **4**, 612 (1957)].

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

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

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

[8] V. S. Barashenkov and B. M. Barabashov, Nucl. Phys. **9**, 426 (1958).

[9] G. Breit and M. L. Rustgi, Phys. Rev. **114**, 830 (1959).

[10] A. Tenore and A. Verganelakis (private communication).

derived by Aleksandrov from neutron scattering. Other possible causes of the enhanced scattering were investigated by Breit and Rustgi[9] who considered the interaction of the neutron magnetic moment with the vacuum polarization field and by Barashenkov and Kaiser[11] who investigated a number of other possibilities. All of the effects considered are small and do not account for the observed angular dependence. The experimental and theoretical data on nucleon polarizability have recently been reviewed by Barashenkov and Kaiser.[11]

The present work was undertaken to explore further the anomalous small-angle scattering and to investigate its possible relation to the electric polarizability of the neutron. Preliminary measurements were made of the small-angle elastic scattering of neutrons from Cu, Pb, and U at 0.57-MeV and at 1.0-MeV neutron energy. Within the 10% relative accuracy of these initial experiments the differential cross sections at 3.6 and 8 degrees were equal, and it was apparent that considerable improvement in the precision of the measurement would be necessary to detect any polarizability effect. Since the polarizability effect is expected to be largest at low neutron energies and to increase with the atomic number of the scattering nucleus, the subsequent effort was devoted to measuring the scattering of 0.57-MeV neutrons from U. This measurement is thus in an energy range comparable to those of Aleksandrov *et al.*,[1,2] but the improved energy resolution of the present experiment reduces the ambiguity of the analysis.

A preliminary report of this experiment has been published previously.[12]

II. EXPERIMENTAL PROCEDURE

The differential cross sections for elastic scattering were measured by observing the neutrons scattered out of a collimated beam of monoenergetic neutrons incident on a scattering sample. The geometry of the experimental arrangement is shown in Fig. 1, which gives the relative positions of the neutron source, the scattering sample, and the detector.

Neutrons were produced by the $\mathrm{Li}^7(p,n)\mathrm{Be}^7$ reaction with protons from a Van de Graaff generator. The lithium targets were about 50 keV thick and were evaporated onto a 0.025-cm gold backing which was cooled by an air jet. Proton beam currents as high as 10 μA could be used without appreciable deterioration of the target. During the experiment and the calibrations, counting rates were measured by recording the number of neutrons counted per run; the duration of each individual run was controlled by a current integrator which ended the run when a predetermined proton charge was collected at the target.

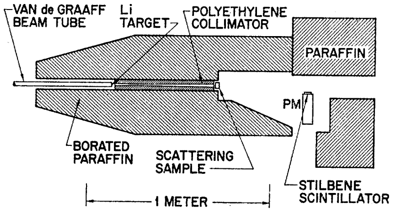

FIG. 1. Geometry of the experimental apparatus.

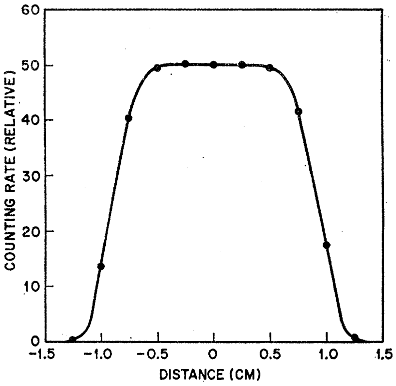

FIG. 2. Profile of the collimated neutron beam as measured at the plane of the detector with a 0.3-cm-wide stilbene scintillator.

Neutrons produced at zero degrees to the incoming proton beam were collimated with a borated paraffin shield and a polyethylene collimator as shown in Fig. 1. The collimator consisted of a series of polyethylene cylinders 5 cm in diameter and 3.8 cm in length, having a combined total length of about 50 cm. The cylinders had center holes of various diameters, and these aligned holes formed the collimator throat. The minimum diameter of the collimator occurred about 12 cm from the target and was 0.5 cm. Between this point and the scattering sample position, the collimator was tapered, reaching a diameter of 1.0 cm at the scattering sample. The profile of the neutron beam emerging from the collimator was measured at the detector position, 55 cm from the collimator exit and is shown in Fig. 2. For this measurement the detector was a stilbene scintillator $0.3\times1.0\times2.0$ cm mounted with its largest face to the photomultiplier tube. The tube axis was perpendicular to the beam collimator, and the detector was moved parallel to the axis of the photomultiplier tube. The profile shown in Fig. 2, which gives the relative counting rate as a function of detector distance from the beam center, accurately represents the geometrical shielding of the collimator. The smallest angle at which cross section measurements were made was 3.6° corresponding to a distance of ≈ 3 cm from the beam center. With no scattering sample in place the ratio of neutron flux at the beam center to the neutron flux at the 3.0-cm position was about 6000.

The spectral purity of the neutrons emerging from the collimator was investigated by pulsing the neutron source and observing the distribution in arrival time

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[11] V. S. Barashenkov and H. J. Kaiser, Fortschr. Physik **10**, 33 (1962).

[12] D. B. Fossan and M. Walt, Phys. Rev. Letters **12**, 672 (1964).

of the detected neutrons. This test indicated that of the neutrons detected, a negligible fraction had suffered energy-loss collisions in the collimator and shield.

The scattering samples consisted of cylinders 1.25 cm in diameter and with lengths chosen to give neutron transmissions of about 65%. The samples were placed with their axes along the axis of the neutron collimator so that all neutrons leaving the collimator aperture entered the scattering samples. These samples were alternately inserted into the beam and removed by a remotely controlled mechanism.

The neutron detector used to observe the scattered neutrons was a stilbene scintillator, 1.0×2.5×3.0 cm which served as a biased proton recoil detector. For the 0.57-MeV measurements the bias was set to exclude neutrons with energies below 0.40 MeV. The scintillator was mounted with its largest face to the photomultiplier and was oriented with its 3.0-cm dimension parallel to the collimator axis (see Fig. 1). The entire detection unit including photomultiplier, discriminator, and preamplifier moved on a track perpendicular to the collimated neutron beam so the stilbene crystal could be conveniently moved into the direct beam and into the beam scattered at various angles. The differential cross sections at 3.6°, 5.9°, 8.2°, and 12.7° were measured with the detector 55 cm from the scattering sample. For larger angles the detector-to-sample distance was reduced to 33 cm and cross sections were obtained at 10.1°, 14.9°, and 18°. Taking into account the source extension, the collimator aperture, and the detector size, the angular resolution for the two geometries was about ±1.5° and ±2° for the long and short distances, respectively.

Gamma-ray discrimination was achieved by a space-charge-limiting technique[13] which utilized the difference in pulse shape between electron- and proton-induced scintillations in the stilbene crystal. The effectiveness of this discriminator was checked with gamma-ray sources and by the observation of neutrons and gamma rays separated by the time-of-flight method. Essentially complete discrimination of gamma rays was obtained.

Cross sections were obtained from the number of neutrons detected at the various angles relative to the number of neutrons incident on the scattering sample. The number of neutrons impinging on the scattering sample was measured by moving the detector in small steps across the direct beam and numerically integrating the resulting profile. Since all neutrons passing through the collimator aperture intersect the sample, a measurement of the total beam at any position behind the collimator gives directly the number of neutrons intersecting the sample. The ratio of counts observed in the scattered beam and in the direct beam, after correction for background and for the other effects discussed below, is directly related to the differential cross section. For angles less than about 5° a significant portion of the neutron background results from neutrons which were scattered in the collimator and which leave the collimator aperture at angles large enough to reach the detector. Since these background neutrons are attenuated as they pass through the scattering sample, the background was measured by observing the counts per run with the scattering sample replaced by a carbon sample of equal transmission. The number of neutrons scattered into the detector by the carbon sample was calculated from the known differential cross section of carbon.[14,7] No small-angle effects from neutron polarizability are expected for carbon because of the low atomic number.

Corrections to the data were made for the presence of inelastically scattered neutrons, for the small variations of detector efficiency with counting rate and with angle of incidence of the neutrons, and for the multiple scattering of neutrons in the scattering samples. The contribution from inelastically scattered neutrons was calculated from the known energy sensitivity of the detector and the differential cross section for inelastic scattering, extrapolated from measurements[15] at larger angles. This correction was approximately 5% of the cross section. The angular response of the detector was measured by rotating the detector in an uncollimated neutron beam and noting the counting rate for neutrons incident at various angles. Over the angular interval used in these measurements the relative efficiency increased by 4% as the angle of incidence varied between 0° and 20°. The counting rate sensitivity of the detector was measured by observing the variation in counting rate with distance from the uncollimated source. Deviations from an inverse-distance-squared dependence were attributed to a reduction in detection efficiency with increased counting rate. For the neutron intensities used the detector efficiency in the direct beam was 0.96 the efficiency in the scattered beam. Although this correction affects the absolute values of the cross sections, it does not influence the angular variation.

Corrections for multiple scattering occurring in the scattering samples were carried out by the Monte Carlo method. In this calculation, the elastic and inelastic cross sections for uranium were taken from experiments of Smith[15] and the differential cross section for the carbon background sample was assumed to be isotropic in the center-of-mass system. For the uranium sample a total of 40 000 neutron histories were traced and the distribution of neutrons arriving at the detector positions after one, two, or three collisions was recorded. From the Monte Carlo results of the number of neutrons incident on the detector after more than one collision in the sample, the ratio of the total neutron count to that produced by singly scattered neutrons was determined. This ratio was applied to the experimental data

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[13] R. B. Owen, Nucleonics **17**, 92 (September 1959).

[14] H. B. Willard, J. K. Bair, and J. D. Kington, Phys. Rev. **98**, 669 (1955).

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

to give the first collision distribution, and from this distribution the differential cross sections were obtained. The numbers of neutrons in the second and third collision distributions obtained from the Monte Carlo method were about 10% and 1%, respectively, of the total distribution. The Monte Carlo results from carbon were used to correct the carbon background data for the contributions of neutrons scattered into the detector by the carbon sample.

III. RESULTS

The differential cross sections for elastic scattering of 0.57-MeV neutrons by natural uranium are given in Table I for angles between 3.6° and 18°. Also given are the probable errors in the absolute values of the measurements. The realtive errors in the various points are about 4% of the cross sections and are caused primarily by statistical uncertainties. The additional error in the absolute values stems from possible nonuniformity in the stilbene scintillator and in the light-collecting efficiency. Since the scattered beam illuminated the entire crystal while the direct beam was observed largely by the central portion, any nonuniform response will affect the ratio of the counting rates obtained for the two situations.

TABLE I. Differential cross sections for elastic scattering of 0.57-MeV neutrons by uranium.

θ (degrees)	$\sigma(\theta)$ (barns)
3.6	1.80 ± 0.15
5.9	1.74 ± 0.15
8.2	1.63 ± 0.12
10.1	1.63 ± 0.11
12.7	1.70 ± 0.13
14.9	1.60 ± 0.11
18.0	1.73 ± 0.12

IV. DISCUSSION

At small scattering angles the principal forces involved in the neutron-nucleus interaction are the specific nuclear force and the interaction of the neutron magnetic moment with the nuclear Coulomb field (Schwinger scattering). In addition to these forces the interaction between an induced electric dipole moment of the neutron and the nuclear Coulomb field may also be appreciable, depending on the magnitude of the neutron polarizability. If the scattering amplitudes for Schwinger scattering and for the neutron polarizability scattering are computed in Born approximation, the differential cross section for elastic scattering of spin unpolarized neutrons is given by

$$\sigma(\theta)=|f_n|^2+2(\mathrm{Re}A)f_p+f_p^2+2(\mathrm{Im}B)\gamma\cot\tfrac{1}{2}\theta+|f_s|^2, \quad (1)$$

where the nuclear scattering amplitude is expressed in the form

$$f_n=A+B(\boldsymbol{\sigma}\cdot\mathbf{n}). \quad (2)$$

The scattering amplitude f_p results from the induced electric dipole moment, and f_s is the Schwinger scattering amplitude. These quantities are given by

$$f_p(\theta)=\tfrac{1}{2}m\alpha\left(\frac{Ze}{\hbar}\right)^2 K\left[\frac{\sin KR}{(KR)^2}+\frac{\cos KR}{KR}+\mathrm{si}(KR)\right] \quad (3)$$

$$f_s(\theta)=i\gamma\cot\tfrac{1}{2}\theta(\boldsymbol{\sigma}\cdot\mathbf{n}), \quad (4)$$

where $K=2k\sin(\theta/2)$ and $\gamma=1.35\times10^{-14}$ cm for uranium. In these expressions, k is the neutron wavenumber, $\mathbf{n}$ is a unit vector normal to the scattering plane, Z is the atomic number of the scattering nucleus, $\boldsymbol{\sigma}$ is the Pauli spin vector, m is the reduced mass of the neutron, and si denotes the sine integral function.

The sensitivity of the differential cross sections to the neutron polarizability α was investigated by evaluating Eq. (1) for various values of α. In this calculation, the nuclear scattering amplitude in terms of the A and B functions was computed for an optical model potential of the form[16]

$$V(r)=-\frac{V_{\mathrm{RE}}}{1+\exp[(r-R)/a]}-iV_{\mathrm{IM}}\exp[-(r-R)^2/b^2]-V_{\mathrm{SR}}\left(\frac{\hbar}{\mu_\pi c}\right)^2\frac{1}{r}\left|\frac{d}{dr}\left(\frac{1}{1+\exp[(r-R)/a]}\right)\right|\mathbf{l}\cdot\boldsymbol{\sigma}, \quad (5)$$

where μ_π is the mass of the π meson and $\mathbf{l}$ is the orbital angular momentum of the incident neutron. The potential well parameters selected by Auerbach and Moore[17] ($V_{\mathrm{RE}}=39.8$ MeV, $V_{\mathrm{IM}}=6.9$ MeV, $V_{\mathrm{SR}}=15.0$ MeV, $R=8.18\times10^{-13}$ cm, $a=0.47\times10^{-13}$ cm, and $b=1.0\times10^{-13}$ cm) were used in the results presented here, although it was found that small variations in these parameters did not greatly influence either the values of ReA or the angular dependence of $|f_n|^2$ at small angles. At 0.57 MeV the nuclear contribution $|f_n|^2$ decreases by about 10% between 0° and 15°.

The effect of the polarizability of the neutron enters through the second and third terms on the right-hand side of Eq. (1), the former term resulting from the interference of the polarizability amplitude with that from nuclear scattering. The polarizability amplitude f_p is positive for small angles and decreases with increasing angle. For heavy elements ReA is negative for $\theta<15°$ and is not affected appreciably by reasonable variations in the optical model parameters. Thus, the neutron polarizability will produce a decrease in the dif-

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[16] We wish to thank Dr. David Saxon for providing us with the computer program SCAT 4 used for these calculations.

[17] E. H. Auerbach and S. O. Moore, Phys. Rev. **135**, B895 (1964).

ferential cross section at small angles if $|2(\mathrm{Re}A)f_p > f_p^2$ and will produce an increase if $|2(\mathrm{Re}A)f_p| < f_p^2$. This destructive interference[18] is illustrated in Fig. 3 in which these two terms are evaluated for various α. Since the absolute value of the cross section will depend largely on the nuclear scattering amplitude f_n, the presence of a polarizability effect can be detected most easily by observing the slope of the differential cross section as a function of angle below about 10°. The comparison of the experimental results with the calculated values is shown in Fig. 4. The experimental points represent the measured cross sections after subtraction of the Schwinger scattering term, $|f_s|^2$ (The interference term $2(\mathrm{Im}B)\gamma\cot\frac{1}{2}\theta$ is negligible), and the errors shown are the relative uncertainties only. The experimental data are consistent with a value of $\alpha \gtrsim 2\times10^{-40}$ cm³. A value of α as large as 4×10^{-40} cm³ is in disagreement with these data.

The present results are of particular interest when compared with the experiments of Aleksandrov at 2 and 2.8 MeV and of Dukarevich and Dyumin at 14.2 MeV. In their experiments a sharp increase in cross section with decreasing angle was noted at angles less than about 11°. We have evaluated Eq. (1) at 2.8 MeV and at 14.2 MeV using optical model values for f_n and find that the destructive interference illustrated in Figs. 3 and 4 also occurs at the higher energies. Therefore with an optical model it is not possible to obtain enhanced scattering by means of the interference term $2(\mathrm{Re}A)f_p$. Any enhancement must come from the f_p^2 term, and a substantially larger value of α is required. To produce the small-angle effects observed by Aleksandrov and by Dukarevich and Dyumin α must exceed 5×10^{-40} cm³, a value excluded by the present experiment.

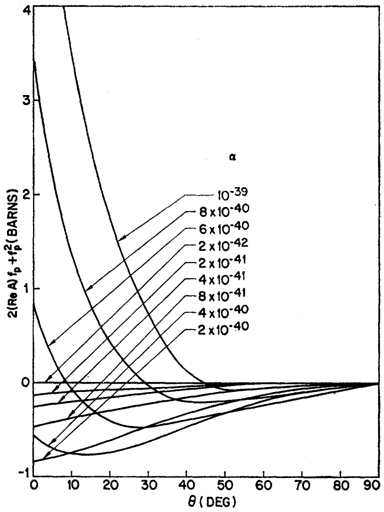

FIG. 3. Calculated contributions to the differential cross section of uranium at $E_n=0.57$ MeV from the electric polarizability of the neutron. The curves give $2(\mathrm{Re}A)f_p+f_p^2$ for the indicated values of the polarizability α.

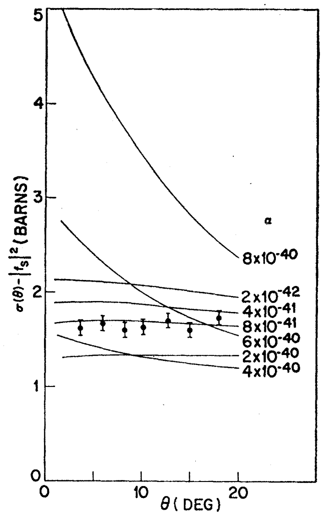

FIG. 4. Comparison of theory and experiment for small angle scattering of 0.57-MeV neutrons from uranium. Experimental points give values of the differential elastic scattering cross section minus the Schwinger scattering. The curves represent the first four terms in Eq. (1).

The result of this analysis differs from that of Aleksandrov who found constructive interference between f_n and f_p and obtained from his data an α equal to $(8\pm3.5)\times10^{-41}$ cm³. Since the optical model calculations reported here result in destructive interference, the difference in the value of α obtained by Aleksandrov and that derived by us from his data is probably due to the difference in nuclear models used.

It is concluded that enhanced small-angle neutron scattering of the magnitude reported at higher energies does not occur at a neutron energy of 0.57 MeV and that the increase in $\sigma(\theta)$ previously observed at small angles is not the result of an induced electric dipole moment in the neutron.

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[18] The destructive nature of the interference between the nuclear scattering and the polarizability scattering was pointed out by V. Weisskopf and H. Feshbach in a private communication referred to by Thaler (Ref. 6).