# Elastic Scattering of 3.1-Mev Polarized Neutrons*

B. M. McCormac,† M. F. Steuer, C. D. Bond,‡ and F. L. Hereford
*Department of Physics, University of Virginia, Charlottesville, Virginia*

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By using a partially polarized neutron beam from the $D(d,n)He^3$ reaction, the elastic scattering polarization of a number of elements has been observed. For Be and C scatterers, the angular dependence of the polarization can be correlated with parameters characterizing compound-nucleus levels excited by the incident neutrons. For medium and heavy scattering nuclei, the observed polarization is in poor agreement with the few existing optical-model calculations for 3.1-Mev neutrons. With the exception of Pb, all medium and heavy elements studied yielded positive polarization in the 30°–60° range of scattering angles, i.e., they would produce polarization in the direction $\mathbf{k}_n \times \mathbf{k}_n'$ in single scattering events.

A NUMBER of experiments have been performed recently in which polarized nucleons were elastically scattered by various nuclei in efforts to obtain information about the spin dependence of nuclear forces.[1] Most of the work has been in the energy range above 100 Mev; however, several workers have studied the scattering of polarized neutrons in the 0.4–3.5 Mev range with interesting results. The effects due to polarization are apparent in a right-left (or azimuthal) asymmetry induced in the scattered intensity, which is customarily expressed[1] by the polarization of the scatterer, $P_{sc}(\theta)$, which the scatterer would produce upon scattering unpolarized neutrons. In the lower energy range, this polarization derives from the spin-orbit coupling contribution to the nucleon-nucleus interaction, known to exist from the success of the shell model.

Following the initial work of Meier *et al.* and others,[2] we recently studied[3] the elastic scattering of 3.1-Mev polarized neutrons [from $D(d,n)He^3$] in $C^{12}$. The observed variation of $P_C(\theta)$ was consistent with the phase-shift analysis of $C^{12}(n,n)$ scattering by Meier *et al.*[2] Upon using a value of carbon polarization computed from the Meier phase shifts, the polarization of the neutrons from $D(d,n)He^3$ was found to be $-0.106 \pm 0.01$ for neutrons emitted at 53° (c.m.) at 600-kev deuteron energy. We consider the direction of positive polarization to be that of $\mathbf{k}_d \times \mathbf{k}_n$, where $\mathbf{k}_d$ and $\mathbf{k}_n$ are the momenta of the incident deuteron and emitted neutron, respectively. This value is in good agreement with that of Meier *et al.*[2] and with recent results of Levintov *et al.*[4]

Using this source of partially polarized neutrons, we have now studied experimentally the polarizations produced by Be, C, Cu, Zr, Sn, and Pb. For each of these scatterers the angular distribution $P_{sc}(\theta)$ was observed in the 30°–135° angular range. In addition, the polarizations for a number of other elements were observed at 30°, 45°, and 60°. Some of the preliminary data have been reported previously.[5]

In the case of the two light elements, we attempt to assess the results in the light of the level parameters corresponding to resonances covered by the incident neutron energy spread. The data for the medium and heavy elements are compared with the few available calculations based upon "complex plus spin-orbit" potentials for the energy region involved.

## EXPERIMENT

The experimental procedure has been described in detail in a previous paper.[3] Briefly, $D(d,n)He^3$ neutrons emitted at 53° (c.m.) bombarded the scatterer, and the intensities of neutrons scattered at various center-of-mass angles, $\theta$, to the right and left were measured simultaneously with differentially biased Stilbene crystals. The "scatterer in" minus "scatterer out" counting rate was taken to represent the scattered neutron intensity. The deuterium target was thick; the incident neutron energy spectrum extended from about 2.8 Mev to 3.3 Mev, the precise range depending upon the incident deuteron energy. The mean energy of the neutrons contributing to the data was further dependent upon the bias on the detectors and was 3.1 Mev for 600-kev incident deuterons. Some of the data were taken with 750-kev deuterons, in which case the mean energy was 3.2 Mev.

The right-left ratio, $R$, yields the product of incident-neutron polarization, $P_n$, with polarization of the scatterer, $P_{sc}(\theta)$, through the relation,

$$P_n P_{sc}(\theta) = \gamma(\theta) \frac{1 - R(\theta)}{1 + R(\theta)}, \tag{1}$$

where $\gamma(\theta)$ is the correction for finite scatterer-detector geometry. Positive $P_{sc}(\theta)$ corresponds to polarization in the direction $\mathbf{k}_n \times \mathbf{k}_n'$. The correction, $\gamma(\theta)$, was computed by a previously described method[3] for both

* Supported by the U. S. Atomic Energy Commission and the Office of Ordnance Research, U. S. Army.

† Now at Office of Special Weapons Development, Fort Bliss, Texas.

‡ Now at Virginia Polytechnic Institute, Blacksburg, Virginia.

[1] L. Wolfenstein, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, pp. 43–76.

[2] Meier, Scherrer, and Trumpy, Helv. Phys. Acta **27**, 577 (1954); R. Budde and P. Huber, Helv. Phys. Acta **28**, 49 (1955).

[3] McCormac, Steuer, Bond, and Hereford, Phys. Rev. **104**, 718 (1956).

[4] Levintov, Miller, Tarumov, and Shamshev, Nuclear Phys. **3**, 237 (1957).

[5] Hereford, McCormac, Steuer, and Bond, Bull. Am. Phys. Soc. Ser. II, **1**, 339 (1956).

the azimuth and zenith detector spans for C and Be. For the other scatterers, correction was made only for the azimuth span, due to lack of sufficient information regarding differential cross sections. The scatterer-detector geometry introduced a scattering angle spread of 22°, which should be borne in mind upon examination of the curves presented below. No effort was made to correct the data for plural scattering within the scatterers, the radii of which were about one-fourth of a neutron mean free path. Instrumental asymmetries were eliminated through observation of $R(\theta)$ for neutrons emitted to both the right and left of the incident deuteron beam (for which cases the direction of $\mathbf{P}_n$ is opposite). The possible influence of low-energy neutrons and gamma rays from inelastic neutron scattering also required consideration. From available inelastic cross-section data and from examination of the "scatterer in" minus "scatterer out" differential pulse-height spectra of our detectors, we were able to estimate the extent to which inelastic scattering contaminated our data. In the case of Be, previous results[6] indicate no detectable inelastic scattering of 3.2 Mev neutrons. For C the scattering was wholly elastic, since the first excited state lies at 4.43 Mev. Among Cu, Zr, Sn, and Pb the greatest inelastic contribution occurs for Pb, for which we estimate the percent contamination to vary from 2% at a 30° scattering angle to 20% at 130°. Presuming this contribution to the counting rates to be isotropic, its effect is to lower the observed right-left asymmetry.

In the curves shown, the polarization of each scatterer is plotted as a function of the c.m. scattering angle. The absolute magnitude of the polarization was obtained through Eq. (1) assuming $P_n=-0.106$. Since $P_n$ was fixed throughout all measurements, the angular distributions $P_{sc}(\theta)$ are independent of possible error in this value of $P_n$.

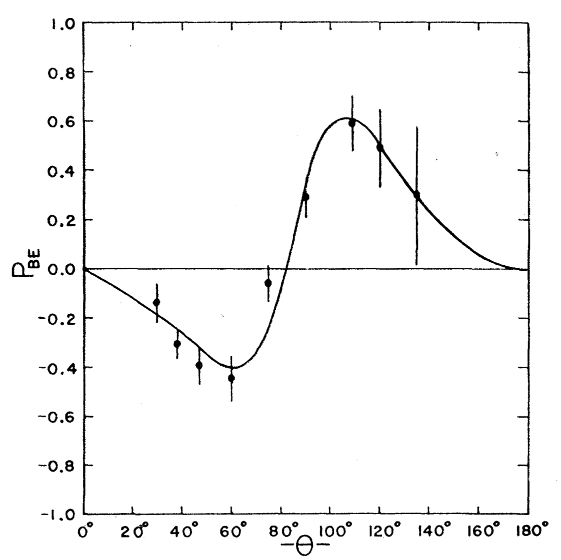


FIG. 1. The Be polarization *vs* center-of-mass scattering angle. The solid curve is Eq. (3) of the text.

[6] Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954); R. B. Day, Phys. Rev. **102**, 788 (1956).

## RESULTS

*Beryllium.*—The data on $P_{\mathrm{Be}}(\theta)$, shown in Fig. 1, show a strong $\sin 2\theta$ component with a maximum degree of polarization $P_{\mathrm{Be}}=0.6$. Previous data[7] on $\mathrm{Be}^9(n,n)$ indicate a narrow resonance at 2.73 Mev overlapped by a much broader one at 2.85 Mev, which is partially covered by our range of incident-neutron energies.

The results have been fitted by an expression given in the Racah formalism by Simon and Welton,[8]

$$P_{sc}(\theta)=\{\sigma_u(\theta)\}^{-1}\sum_{n=1}^{\infty} C_n P_n{}^1(\cos\theta), \qquad (2)$$

where $\sigma_u(\theta)$ is the differential cross section for unpolarized neutrons. The relations between the coefficients $C_n$ and the phase shifts $\delta_{l\pm\frac{1}{2}}$ are readily obtainable and are given by Meier *et al.*[2] By using an extrapolation between the differential cross-section data of Meier and Ricamo[9] (at 2.95 Mev) and Walt and Beyster[10] (at 4.1 Mev) for unpolarized neutrons, the Be data have been fitted by the solid curve in Fig. 1, which is

$$P_{\mathrm{Be}}(\theta)=\{\sigma_u(\theta)\}^{-1}\{6P_1{}^1-44P_2{}^1 -13P_3{}^1+5P_4{}^1\}\times 10^{-3}. \qquad (3)$$

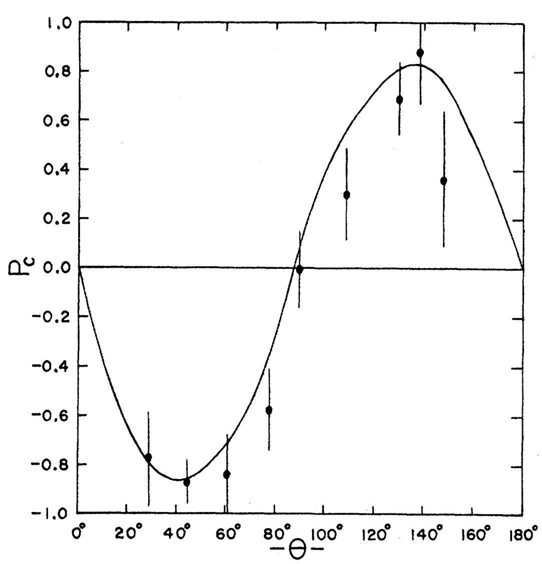


FIG. 2. The C polarization *vs* c.m. scattering angle. The solid curve is the expected polarization computed from the $\mathrm{C}^{12}(n,n)$ phase shifts of Meier *et al.*[2]

[7] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).
[8] A. Simon and T. Walton, Phys. Rev. **90**, 1036 (1953).
[9] R. W. Meier and R. Ricamo, Helv. Phys. Acta **26**, 430 (1953).
[10] M. Walt and J. R. Beyster, Phys. Rev. **98**, 677 (1955).

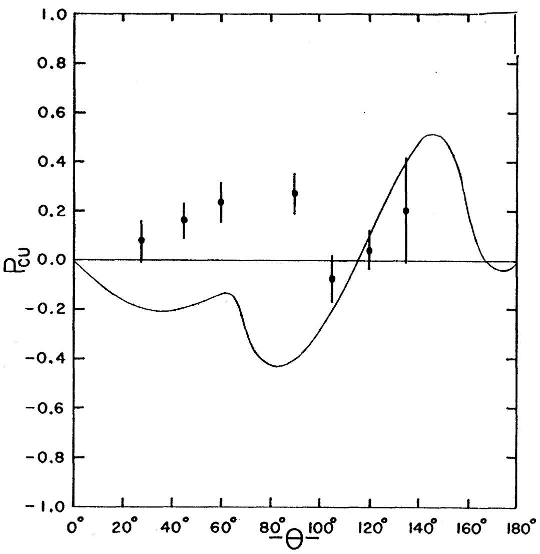


FIG. 3. The Cu polarization *vs* c.m. scattering angle. The solid curve is an optical-model calculation of Remund.[11]

The dominant term is the second, which is probably due to interference between a $D_{\frac{3}{2}}$ broad resonance at 2.85 Mev and $S_{\frac{1}{2}}$ hard-sphere scattering. We assume the $S_{\frac{1}{2}}$ phase shift to be negative, the $D_{\frac{3}{2}}$ phase shift to be positive.

*Carbon.*—The carbon data, given in Fig. 2, also show a strong $\sin 2\theta$ dependence. The phase-shift analysis of Meier *et al.*[2] for $C^{12}(n,n)$ scattering indicates two $D_{\frac{3}{2}}$ resonances at 2.95 Mev and 3.5 Mev. The polarization data can be compared directly with the prediction of this analysis. Detailed calculation of the coefficients, $C_n$, and of the differential cross section $\sigma_u(\theta)$ from the Meier phase shifts yields from Eq. (2).

$$P_C(\theta)=\{\sigma_u(\theta)\}^{-1}\{21P_1^1-131P_2^1-3P_3^1-6P_4^1\}\times 10^{-3}.$$

This expression is plotted in Fig. 2 (solid line); the experimental results are in satisfactory agreement with the curve. On the other hand, the $C^{12}(n,n)$ phase shifts of Budde and Huber[2] predict a much larger $P_1^1(\theta)$ component than the experimental data indicate.

*Copper.*—The observed values of $P_{Cu}(\theta)$ are shown in Fig. 3 and are compared with an optical-model calculation of Remund.[11] This calculation was based upon the following potential:

$$V(r)=\begin{cases} -[42+1.2i+\mathbf{L}\cdot\mathbf{S}]\ \text{Mev}; & r<1.45A^{\frac{1}{3}}\times 10^{-13}\ \text{cm.} \\ 0; & r>1.45A^{\frac{1}{3}}\times 10^{-13}\ \text{cm.} \end{cases}$$

Remund has also reported experimental values of the polarization of Cu and a few other elements. The standard deviations of his measured values are five to ten times the magnitude of those reported here; hence, comparison with his experimental results is not very meaningful, and is not shown in Fig. 3. No agreement between theory and experiment is apparent. However, one should not expect a square-well potential to prove very realistic.

*Zirconium.*—Figure 4 shows the data for Zr, which apparently has very nearly zero polarization throughout the 30°–130° angular range. No computed curves were available for comparison in this instance.

*Tin.*—The data for Sn appear in Fig. 5 and are compared with the results of an optical-model calcu-

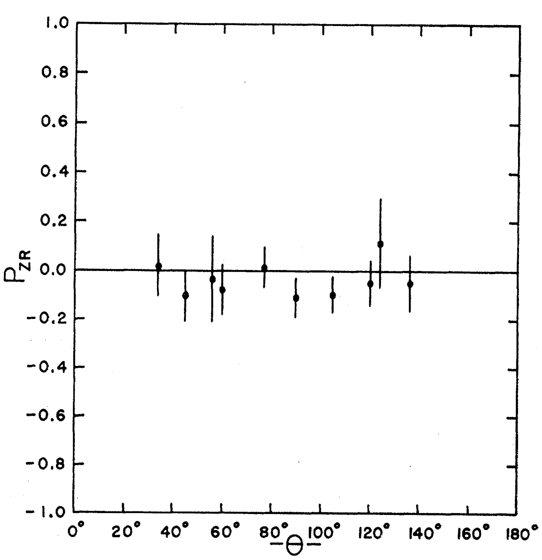


FIG. 4. The Zr polarization *vs* c.m. scattering angle.

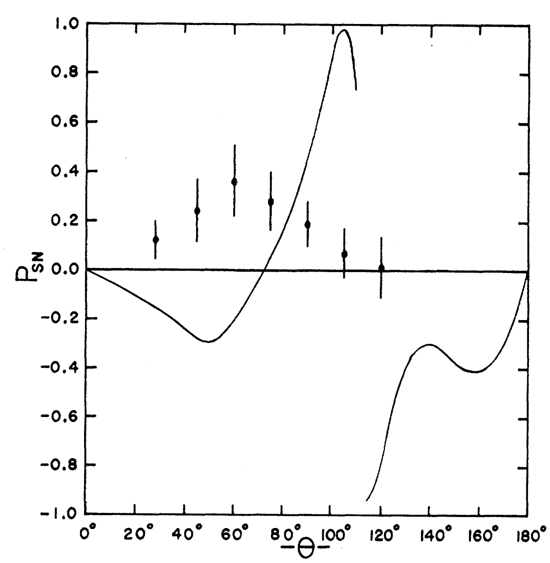


FIG. 5. The Sn polarization *vs* c.m. scattering angle. The solid curve is an optical-model calculation of Bjorklund.[12]

[11] A. Remund, Helv. Phys. Acta **29**, 545 (1956).

TABLE I. Polarization of scatterers at 30°, 45°, and 60° scattering angles.

| Scatterer | Polarization (%) $\theta=30°$ | $\theta=45°$ | $\theta=60°$ |
|---|---|---|---|
| Be | $-13\pm5$ | $-39\pm6$ | $-44\pm8$ |
| C | $-77\pm18$ | $-85\pm9$ | $-83\pm17$ |
| O | $78\pm9$ | $83\pm6$ | $55\pm8$ |
| Mg | $33\pm15$ | $37\pm11$ | $52\pm22$ |
| Mn | $-5\pm17$ | $9\pm11$ | |
| Fe | $1\pm11$ | $8\pm12$ | $8\pm10$ |
| Cu | $8\pm8$ | $17\pm7$ | $23\pm8$ |
| Zn | | $22\pm13$ | $6\pm17$ |
| Zr | $2\pm10$ | $-10\pm8$ | $-7\pm9$ |
| Mo | $34\pm13$ | $34\pm16$ | $35\pm17$ |
| Sn | $12\pm7$ | $25\pm12$ | $37\pm14$ |
| Pb | $-29\pm9$ | $-16\pm8$ | $10\pm10$ |
| Th | $34\pm11$ | | |
| U | $50\pm10$ | | |

lation of Bjorklund.[12] The potential employed was that yielding the best fit of 7- and 14-Mev differential cross-section measurements with a spin-orbit term added (of magnitude 39.5 times the Thomas term),

$$V(r)=-V_1\left[1-\exp\left(\frac{r-r_0}{a}\right)\right]^{-1}-iV_2\exp\left[-\left(\frac{r-r_0}{b}\right)^2\right]-\frac{\lambda\hbar^2}{4m^2c^2}\frac{1}{r}\left(\frac{dU}{dr}\right)\boldsymbol{\sigma}\cdot\mathbf{L},$$

$$V_1=44 \text{ Mev},\quad V_2=9.5 \text{ Mev},$$

$$U(r)=V_1\left[1-\exp\left(\frac{r-r_0}{a}\right)\right]^{-1},$$

$$a=0.65,\quad b=0.98,$$

$$\lambda=39.5,\quad r_0=1.27A^{\frac{1}{3}}\times10^{-13} \text{ cm}.$$

Again the data are in poor agreement with the theoretical curve.

*Lead.*—The results for Pb in Fig. 6 are in equally poor agreement with the optical-model calculations of both Remund and Bjorklund. We do not feel that this discrepancy should be viewed seriously. Wide variations can be introduced in the polarization computed on the optical-model basis without appreciably altering the differential cross section for unpolarized neutrons. Also, at 3.1 Mev there is likely to be a significant compound elastic contribution.

[12] F. Bjorklund (private communication).

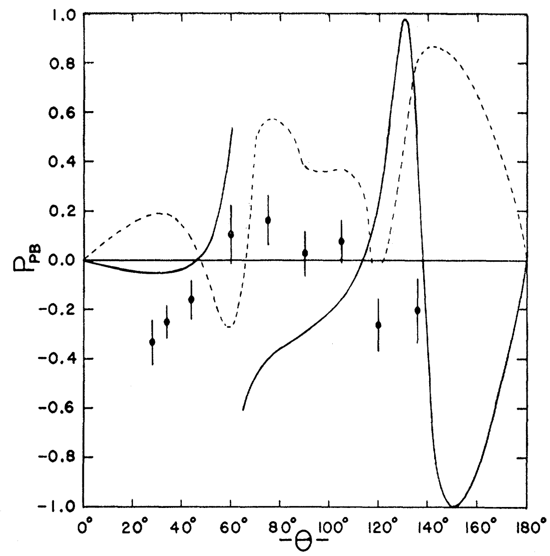


FIG. 6. The Pb polarization *vs* c.m. scattering angle. The solid and dashed curves are, respectively, optical-model calculations of Bjorklund[12] and Remund.[11]

We have also measured the polarizations of a number of other elements at scattering angles 30°, 45°, and 60°. The results are presented in Table I. In the case of these scatterers, the inelastic scattering contamination of the counting rates was estimated to be at the most 10%.

## ACKNOWLEDGMENTS

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