Elastic Scattering of Polarized 2.8-Mev Neutrons*

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The polarization produced in the elastic scattering at 90° of partially polarized 2.8-Mev neutrons by C, Mg, Al, Ni, and Cu has been measured. All yield positive polarization. The polarizations produced by Ni and Cu are nearly the same whereas those produced by Al and Mg are very different. The polarization observed for carbon is in agreement with calculations from available phase-shift data.

INTRODUCTION

A NUMBER of experiments have been performed[1–5] to study the polarization produced in the elastic scattering of partially polarized neutrons from $Li^7(p,n)Be^7$ and $D(d,n)He^3$ neutrons in the energy range 380 kev to 3.4 Mev. At 380- and 980-kev neutron energy the polarization produced has been studied[5] as a function of mass number at three scattering angles. Recently, Rosen[6] reported measurements (by Cranberg) of the polarization produced in the elastic scattering of 2.1-Mev neutrons by a number of elements at three scattering angles. The polarization of a few elements has been measured by McCormac *et al.* at 3.1 Mev, by Remund at 3.3 Mev, and by Hereford[7] at 3.4 Mev.

We have measured the polarization produced in the scattering of 2.8-Mev neutrons at 90° by C, Mg, Al, Ni, and Cu.

Effects due to polarization produced in the scattering are apparent in an azimuthal asymmetry induced in the scattered intensity. This asymmetry is proportional to the polarization of the scatterer $P_{sc}(\theta)$, i.e., the polarization which the scatterer would produce upon scattering unpolarized neutrons.

EXPERIMENT

The experimental arrangement is shown in Fig. 1. Neutrons were produced by bombarding a thick deuterated titanium target with deuterons of energy 175 kev; those emitted at 49° to the deuteron beam passed through the collimator and were used for scattering. Since a thick target was used the energy of the neutrons produced ranged from 2.50 to 2.82 Mev. Elements of high chemical purity in the form of solid cylinders were used as scatterers. The radii of carbon and aluminum samples were about $\frac{1}{3}$ of a mean free path for 2.8-Mev neutrons, those of nickel and copper about $\frac{1}{2}$ a mean free path, whereas that of magnesium was about $\frac{1}{5}$ of a mean free path. Neutrons scattered at 90° were detected by a 1-inch cube of plastic scintillator mounted on an RCA 6342A photomultiplier. The same detector was used alternately to count the number scattered to the right and left. Neutrons from the source were monitored by a thin stilbene scintillator of 1 in.×1 in.×0.2 in. The direction of positive polarization is taken as $\mathbf{k}_d\times\mathbf{k}_n$ for the incident neutron and $\mathbf{k}_n\times\mathbf{k}_n'$ for the scattered neutron. The positions of the detector referred to as "right" and "left" are shown in Fig. 2. The scatterer-detector geometry produced a scattering angle spread of $\lesssim 25°$.

The differential cross section for scattering of polarized neutrons is given by

$$\sigma(\theta,\varphi)=(1+\mathbf{P}_n\cdot\mathbf{P}_{sc}), \qquad (1)$$

where $\mathbf{P}_n\cdot\mathbf{P}_{sc}=P_nP_{sc}\cos\varphi$. P_n is the polarization of the incident neutron, P_{sc} the polarization of the scattered neutron (referred to as the polarization of the scatterer),

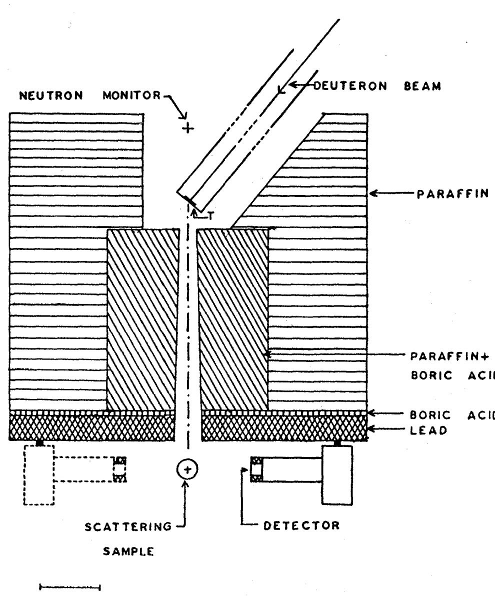

FIG. 1. Experimental arrangement used for a scattering angle of 90°. T is the deuterated titanium target.

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[1] R. K. Adair, S. E. Darden, and Fields, Phys. Rev. **96**, 503 (1954).
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[3] A. E. Remund, Helv. Phys. Acta. **29**, 545 (1956).
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[5] J. D. Clement, F. Boreli, S. E. Darden, W. Haeberli, and H. R. Streibel, Nuclear Phys. **6**, 177 (1958).
[6] L. Rosen, *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 185.
[7] F. L. Hereford, *Proceedings of the International Symposium on Polarization Phenomena of Nucleons, Basel, 1960*, edited by P. Huber and K. P. Meyer (Berkhauser Verlag, Basel and Stuttgart, 1961), p. 303.

and φ the azimuthal angle. The asymmetry, e, defined as

$$e=(R-L)/(R+L), \tag{2}$$

is then equal to $P_nP_{sc}(\theta)$.

From a knowledge of P_n and a measurement of the asymmetry the polarization of the scatterer, $P_{sc}(\theta)$, corresponding to the scattering angle θ can be evaluated.

Several tests were conducted to ensure that no unknown experimental asymmetries were introduced into the measurements. It is easy to see from (1) that at $\varphi=90°$ and $270°$ $\sigma(\theta,\varphi)$ is independent of φ and therefore asymmetry in this plane must be zero. Neutrons scattered in the plane at right angles to the $D(d,n)He^3$ reaction plane should therefore exhibit no right-left asymmetry. The asymmetry in this plane was checked and found to be negligible. According to phase-shift analysis of Meier *et al.*[8] of neutrons scattered by carbon, $P_C \simeq -\sin 2\theta_{c.m.}$, where P_C is the polarization of carbon, and $\theta_{c.m.}$ is the center-of-mass scattering angle of neutrons by carbon. The polarization of neutrons scattered by carbon at $\theta_{c.m.}=90°$ must therefore be nearly zero and so the asymmetry. The asymmetry of neutrons scattered by carbon at $\theta_{c.m.}=90°$ was measured and found to be 0.004 ± 0.011.

These two tests ensured the elimination of instrumental asymmetries. To be certain that no asymmetries were introduced in the course of measurements, which extended over several days, the azimuthal asymmetry in the scattering of neutrons by carbon at $\theta_{c.m.}=90°$ was measured periodically.

The measured asymmetries are subject to a number of corrections. These arise from (1) variation of polarization of neutrons with emission angle, (2) variation of neutron flux across the scatterer, (3) small differences in the scatterer-detector distance on the two sides, (4) the effect of multiple scattering, and (5) finite size of scatterer and detector. The first three corrections are generally small and can be applied in a straightforward manner. However, corrections for multiple scattering and spread in the scattering angle are not easy to estimate. It is easy to apply a correction for the finite spread in the azimuthal angle. Brullmann *et al.*[9] give an approximate treatment for estimation of multiple scattering. Since only protons counted in a narrow energy interval in the highest energy region were used for calculating the asymmetries, the effect of multiple scattering is believed to be quite small and far less than the value estimated from Brullmann's expression, which assumes that neutrons of all energies are detected with equal efficiency. An expression to estimate the correction applicable on account of the finite size of the scatterer and detector has been derived by McCormac *et al.*[10] for the case of carbon, where

$$P_{sc}(\theta)=-\sin 2\theta. \tag{3}$$

The expression turns out to be a function of $\sigma_u(\theta)$, $\sigma_u'(\theta)$, and $\sigma_u''(\theta)$ where the latter are differential cross section and its derivatives with respect to l_3, i.e., $\sigma_u'(\theta)=(\partial\sigma_u(\theta)/\partial l_3)_{l_3=\lambda_3}$. All the quantities referred to here have the same meaning as those of McCormac *et al.* For those cases for which $P_{sc}(\theta)$ does not have the $\sin 2\theta$ dependence the expression for correction turns out to be a function of $\sigma_u(\theta)$, $P_{sc}(\theta)$, and their derivatives. So the correction factor cannot be evaluated without knowledge of these. Since, for the elements studied, neither $\sigma_u(\theta)$ nor $P_{sc}(\theta)$ are available in the energy range of interest here, no attempt was made to apply any correction to the asymmetry for finite scattering angle spread. Corrections are applied for spread in the azimuthal angle only.

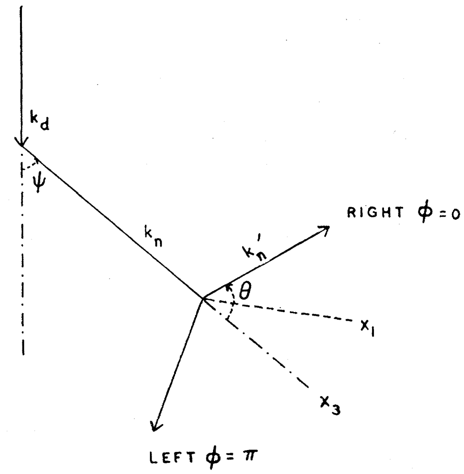

FIG. 2. Diagram illustrating the sign convention adopted in the text. $\mathbf{k}_d$, $\mathbf{k}_n$, and $\mathbf{k}_n'$ represent the momenta of the deuteron, produced neutron, and scattered neutron, respectively. ψ refers to the emission angle of the neutron from the $D(d,n)He^3$ reaction and θ refers to the scattering angle of the neutron. The position θ, $\varphi=0$ is referred to as "right" and θ, $\varphi=\pi$ as "left". The direction of positive polarization of the neutron $\mathbf{P}_n(\phi)$, and the polarization produced due to scattering by the scatterer $\mathbf{P}_{sc}(\theta)$ are taken as $\mathbf{P}_n(\phi)=\mathbf{k}_d\times\mathbf{k}_n/|\mathbf{k}_d\times\mathbf{k}_n|$ and $P_{sc}(\theta)=\mathbf{k}_n\times\mathbf{k}_n'/|\mathbf{k}_n\times\mathbf{k}_n'|$.

A degree of uncertainty in the measured polarizations arises as a result of the influence of low-energy neutrons and gamma rays from inelastic neutron scattering on the measured counting rates. Only pulses in a narrow energy interval in the highest pulse-height region were accepted for calculating the asymmetries and the energy interval selected was narrower than the separation between the ground state and the first excited state of the scattering nucleus. The first excited states of the scattering nuclei studied are at about 800 kev. Gamma rays from this level produce few pulses in the proton pulse-height interval used for calculating asymmetries. The uncertainty of the measured polarizations due to inelastic neutron scattering is therefore thought to be small. Presuming inelastic scattered neutrons and de-excita-

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TABLE I. Polarization values.

Element	Scattering angle θ	This experiment[a] Measured $P_nP_{sc}\times10^3$	P_{sc} (%) (corrected)	Comparison values $P_{sc}{}^{b}$ (%) $\bar{E}_n=3.1$ Mev	$P_{sc}{}^{c}$ (%) $\bar{E}_n=3.3$ Mev	$P_{sc}{}^{d}$ (%) $\bar{E}_n=3.4$ Mev	Calculated from phase-shift data [e]	[f]
Carbon	90° c.m.	2 ± 11	-7 ± 18	0 ± 14			24	16
Carbon	90° lab	-51 ± 10	80 ± 17	36[g]			72	67
Magnesium	90° lab	-81 ± 26	100_{-13}^{+0}					
Aluminum	90° lab	-40 ± 15	63 ± 25					
Nickel	90° lab	-32 ± 14	53 ± 23					
Copper	90° lab	$-25\pm\ 9$	38 ± 15	30 ± 10	29 ± 50	40 ± 10		

[a] Average neutron energy =2.8 Mev; neutron emission angle =49° in the laboratory; P_n at $\bar{E}_d$ =kev is (-6 ± 2.5)%.
[b] See reference 4.
[c] See reference 3.
[d] See reference 7.
[e] See reference 8 ($\bar{E}_n=2.8$ Mev).
[f] See reference 14 ($\bar{E}_n=2.76$ Mev).
[g] Interpolated value from the curve of $P_C(\theta)$ versus θ.

tion gammas to be isotropic, one concludes that the effect of inelastic scattering is to lower the observed asymmetries.

The polarization of $D(d,n)He^3$ neutrons at a deuteron energy of 93 kev for a thick target has been measured by Kane[11] to be (-10.6 ± 2.3)% and by Pasma[12] at 200 kev to be (-5.8 ± 2.5)%. These two values do not agree well. Kane cites extensive evidence in support of his value and also points to the large relative statistical error in the value measured by Pasma. Pasma and several others have measured the polarization of $D(d,n)He^3$ neutrons using thin targets whereas Kane has measured the polarization using a thick target. Considering the thin-target and thick-target results published by various authors, Kane concludes that the polarization of $D(d,n)He^3$ neutrons is independent of the deuteron energy between 93 kev and 700 kev. H. Brinkman[13] has challenged the conclusions and measurements of Kane on the basis of the systematic trend of observed values in the energy range from 200 kev to 1.800 Mev. In view of this we assume a value of (-6 ± 2.5)% for the polarization of neutrons from the $D(d,n)He^3$ reaction produced by deuterons of mean energy 130 kev.

[11] P. P. Kane, Nuclear Phys. **10**, 429 (1959).
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[13] H. Brinkman, *Proceedings of the International Symposium on Polarization Phenomena of Nucleons, Basel, 1960,* edited by P. Huber and K. P. Meyer (Berkhauser Verlag, Basel and Stuttgart, 1961), p. 166.

RESULTS AND CONCLUSIONS

Experimental results are presented in Table I and compared with existing data. Polarization obtained for C is to be compared with those calculated from phase-shift data of Meier *et al.* and Wills *et al.*[14] No values are available for the polarization of neutrons scattered by Al and Ni in this energy region. The value obtained for Cu is nearly the same as those of McCormac *et al.* at 3.1 Mev, Remund at 3.3 Mev, and Hereford at 3.4 Mev. The fact that nearly the same polarization is obtained for Cu at a scattering angle of 90° by several investigators at different neutron energies in the range 2.8 to 3.4 Mev suggests a very slow variation of polarization with energy. The observation reported here, of nearly the same values of polarization for Ni and Cu, and the slow variation suggested by the data at several energies, are in accord with that expected on the basis of the optical model. The similarity of polarization values for Cu and Ni also suggests no strong dependence of polarization on the spin of the scattering nucleus.

The large difference in the polarizations of the neighboring nuclei Mg and Al (both light) is believed to be due to insufficient averaging of levels in the compound nucleus. Similar fluctuations in the polarization of neighboring elements below $A=100$ has been observed by Clement *et al.* at neutron energies of 380 and 980 kev.

[14] J. E. Wills, Jr., J. K. Bair, H. O. Cohn, and H. B. Willard, Phys. Rev. **109**, 891 (1958).