Scattering of Polarized Neutrons from Heavy Nuclei*

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The polarization of 400-kev Li(p,n) neutrons emitted at a laboratory angle of 50° with respect to the incident proton beam was measured to be 53±6 percent by determining the left-right asymmetry in the intensity of neutrons scattered at 90° from oxygen. Oxygen scattering phase shifts necessary for this calculation were derived from the results of previous experiments.

Left-right scattering asymmetries were measured for 11 elements, ranging in atomic weight from copper to bismuth. From these asymmetries the magnitudes of the polarizations caused by the heavy nuclei were determined. The variation of the polarization with atomic number appeared similar to that expected from the square well-with-absorption nuclear model of Feshbach, Porter, and Weisskopf, modified by the addition of a spin-orbit term equal to -1.5 Mev ($\mathbf{l}\cdot\mathbf{s}$).

I. INTRODUCTION

FESHBACH, Porter, and Weisskopf[1] have shown that the results of measurements of the total neutron cross sections of nuclei as a function of atomic number and of neutron energy[2–4] are in good agreement with the predictions of a simple nuclear model. Furthermore, observed angular distributions of elastically scattered neutrons have been found to be similar to predictions employing this model.[5,6] The model uses a square well with a range of $1.45\times10^{-13}\,A^{\frac{1}{3}}$ cm and a depth $V_0(1+i\zeta)$, where v_0 is taken as 19 Mev and ζ, which represents the effect of absorption of the neutron to form a compound state, is equal to 0.05. Such a description of the nucleus appears reasonable in view of the success of the independent particle model,[7,8] since the small absorption coefficient, ζ, results in a long mean-free path of the nucleon in nuclear matter. In addition to assuming the presence in the nucleus of single-particle orbits, the shell model introduces spin-orbit coupling. It appeared desirable to investigate the presence and strength of the nuclear spin-orbit forces which would be expected to have an effect on scattering in addition to their effect on bound states[7,8] of nuclei. The spin-orbit forces will affect the angular distributions of neutrons scattered from nuclei and the variation of total neutron cross sections with energy. It would be difficult, however, to deduce the effect of spin-orbit forces from measurements of these quantities. On the other hand, the presence of spin-orbit forces can be observed in a reasonably unambiguous manner by measuring the polarization of neutrons scattered from nuclei.[9,10] The magnitude of the polarization and the variation with nuclear size should provide information concerning the strength of spin-orbit forces.

II. PRODUCTION AND ANALYSIS OF POLARIZED NEUTRONS

Polarizations P resulting from scattering of neutrons by heavy nuclei were determined by measuring the left-right asymmetry in the scattering of neutrons, which have an initial polarization P'. The neutrons, scattered through an angle ϑ, were observed in a plane perpendicular to the direction of polarization of the incident beam. The left-right asymmetry, which is the ratio of the neutron flux scattered to the right to that scattered to the left, will be

$$(1+PP')/(1-PP'). \qquad (1)$$

In order to achieve sufficient intensity it appeared desirable to use polarized neutrons produced by a nuclear reaction rather than by scattering. Since the effects of polarization are present only in the interaction of neutrons having an orbital angular momentum greater than zero, fast neutrons must be used; on the other hand, interpretation of any observed effects in scattering is much simpler if the neutron energy is so low that only neutrons with low orbital angular momenta are strongly affected by the interaction. At neutron energies near 500 kev, only S and P waves will be important. Further, a study of the 19.8-Mev excited state of Be^8 indicated[11] that it was probable

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[9] Nucleon polarization has been discussed theoretically by J. Schwinger, Phys. Rev. **69**, 681 (1946); L. Wolfenstein, Phys. Rev. **75**, 1664 (1949); J. Lepore, Phys. Rev. **79**, 137 (1950); R. S. Blin-Stoyle, Proc. Phys. Soc. (London) **64**, 700 (1951); A. Simon and T. A. Welton, Phys. Rev. **90**, 1036 (1953); and others. The calculations in this paper were made following procedures of Wolfenstein.
[10] E. Baumgartner and P. Huber, Helv. Phys. Acta **26**, 420, 545 (1953); R. Ricamo, Helv. Phys. Acta **26**, 423 (1953); R. Ricamo, Nuovo cimento, **10**, 12, 1607 (1953).
[11] R. K. Adair, Phys. Rev. (to be published).

that the Li(p,n) reaction produces, at certain angles, strongly polarized neutrons of about this energy.

Since it is not possible to calculate reliably the magnitude of the polarization of the neutrons from the Li(p,n) reaction, it was necessary to find a suitable analyzer to measure the polarization. There is a neutron scattering resonance of oxygen, at about 435-kev neutron energy associated with a state in O^{17} of spin 3/2 and odd parity.[12] At this neutron energy the only scattering phase shifts expected to be important are the S and $P_{\frac{3}{2}}$ phases. From slow neutron interference measurements the S-wave phase shift, δ_0, is known to be negative. Its magnitude is easily calculable as a function of energy using the relation

$$\sigma=4\pi k^{-2}\sin^2\delta_0, \tag{2}$$

where σ is the nonresonant scattering cross section. The $P_{\frac{3}{2}}$ phase shift can be calculated using the relation[13]

$$\delta(P_{\frac{3}{2}})=\delta_+=\tan^{-1}(\Gamma/2(E_r-E)), \tag{3}$$

where $\Gamma=\Gamma_r x^3(1+x_r^2)/[x_r^3(1+x^2)]$. In this expression Γ represents the width of the resonance, equal to 42 kev at resonance; E_r is the resonance energy, 435 kev; x stands for kR, where R is the nuclear radius taken as 5×10^{-13} cm; and k is the neutron wave number. The subscript r denotes the value of a quantity at the resonance energy. At 90° in the c.m. system, the polarization of neutrons scattered in the neighborhood of this resonance will be equal to

$$P=\frac{2\sin\delta_0\sin\delta_+\sin(\delta_+-\delta_0)}{\sin^2\delta_++\sin^2\delta_0}, \tag{4}$$

where P refers to polarization of the neutron spin in the X direction, for neutrons scattered in the Y direction. The direction of the incident unpolarized beam is taken in the Z direction. The solid curve in Fig. 1 shows the polarization of neutrons scattered at 90° from oxygen as a function of neutron energy calculated using Eqs. (2), (3), and (4). The large values of the polarization make oxygen a useful analyzer of polarized neutrons in this energy region.

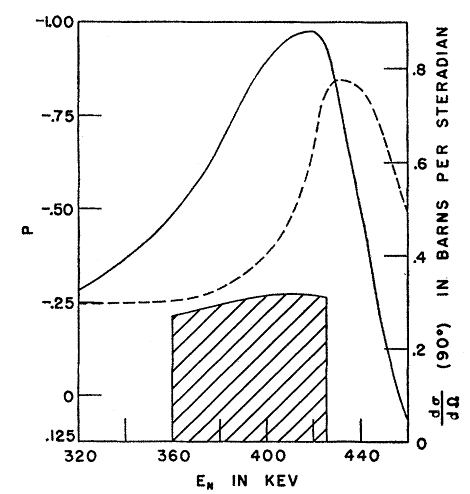

FIG. 1. Curves used to calculate Li(p,n) polarization from oxygen scattering data. The ruled area represents the shape of the neutron energy spectrum from the Li(p,n) reaction as it was used in the measurement. The solid curve shows the polarization of neutrons scattered at 90° in the c.m. system from oxygen, and the dashed curve represents the oxygen differential scattering cross section at 90°, all as a function of neutron energy.

A schematic diagram of the experimental arrangement used to measure the polarization of Li(p,n) neutrons is shown in Fig. 2. Protons from the electrostatic generator with an energy of 2.262 Mev strike a thin lithium target evaporated in place, which has a stopping power of 65 kev for protons of this energy. Neutrons emitted at a laboratory angle of 50° with respect to the incident proton beam pass through a collimating hole in the paraffin shield, and strike a thin-walled metal Dewar filled with liquid oxygen. Neutrons scattered at 90° in the c.m. system by the Dewar and oxygen are counted by a hydrogen recoil proportional counter. Intensity of the scattering by the oxygen was determined by finding the counting rate with the Dewar full and subtracting the background counting rate measured with the Dewar empty. This background counting rate was about 60 percent. The neutron beam was monitored by measuring the charge incident on the lithium target with a current integrator.

The paraffin shield was designed to block the direct beam from the counter and to shield the counter from as much of the room scattered flux as possible. Collimation of the neutron beam was such that the beam did not strike any part of the shield exposed to the counter. A metal Dewar constructed with an inside wall of 0.005-in. stainless steel and an outside wall of 0.015-in. brass served to contain the liquid oxygen. The inside diameter of the Dewar was 1.3 cm and the inside depth was 12 cm. The height of the liquid oxygen column would stay above 7 cm for about 15 minutes after filling. Since the diameter of the neutron beam was 5 cm, measurements could be made safely for nearly 15 minutes without refilling the Dewar. A recoil proportional counter filled with 4 atmos of hydrogen, and having an active volume 2.5 cm in diameter and about 10 cm long, was used as a neutron detector. Counts were recorded at two discriminator settings. One discriminator was set to count all pulses from proton recoils of energy greater than 250 kev, the other was biased at 175 kev.

The scatterers were placed about 25 cm from the neutron source. This position was reproducible within 2 mm. The position of the center of the active volume of the counter was about 10 cm from the scatterer

[12] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949); R. K. Adair, Phys. Rev. **92**, 1491 (1953).

[13] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).

and was reproducible within 1 mm. In order to ascertain that no pronounced asymmetries would result from a difference in the effective geometry of the experiment when the counter was moved from one side to the other, the left-right asymmetry in the scattering of neutrons from carbon was measured. Since there is no broad P-wave or D-wave resonance for the scattering of neutrons from carbon near this energy, it is probable that the contribution to the scattering of neutrons with angular momentum greater than zero is small, and hence that there is no appreciable polarization of the scattered neutrons. Therefore, the measured left-right asymmetry of 1.000 ± 0.029 indicates that the experimental procedure introduces no strong bias. For the oxygen scatterer the measured left-right asymmetry was 1.92 ± 0.12. From this value, corrected for multiple scattering, and the oxygen polarization, plotted in Fig. 1, one can calculate the average polarization of the beam of neutrons from the Li(p,n) reaction using Eq. (1). The asymmetries were corrected for multiple scattering following the procedure used by Walt.[14,15] Corrected for mutiple scattering, the left-right asymmetry in the scattering from oxygen is $2.52_{-0.30}^{+0.35}$, where the error includes the uncertainty in the multiple scattering correction and estimated errors in the alignment and geometry. Neutrons multiply scattered into the counter first by the scatterer and then by the paraffin shield will lose, on the average, enough energy so that they will not be counted. If an appreciable number were counted, the counting efficiency will be higher for the low bias than the high bias. Since both biases gave about the same left-right asymmetry, it appears that effects caused by neutrons scattered by the shield are not important.

The effective polarization produced by the oxygen scatterer is an average over the neutron energy spread, weighted according to the differential Li(p,n) cross section at a laboratory angle of 50°, and according to the oxygen scattering cross section at 90°. Both the neutron energy spectrum calculated from the Li(p,n) reaction cross sections measured by Taschek and Hemmendinger[16] and the oxygen scattering cross section at 90°, calculated from the phase shifts of Eqs. (2) and (3), are shown in Fig. 1. By taking P, the average polarization from the oxygen scattering, as -0.82, a value which is a little smaller than the average taken from Fig. 1 because of the small deviation from 90° of most of the neutrons scattered into the counter, a polarization of -0.53 ± 0.06 for the neutron beam from the Li(p,n) reaction was obtained. This value is somewhat higher than a value of -0.35 deduced from theoretical considerations.[11] Although some of the neutrons in the beam from the collimation hole will have been scattered at small angles from the paraffin walls of the collimater, no correction was made for this effect as such collisions will not depolarize the neutrons.

[14] Martin Walt, thesis, University of Wisconsin, 1953 (unpublished).
[15] M. Walt and H. H. Barschall, Phys. Rev. 93, 1062 (1954).
[16] R. F. Taschek and A. Hemmendinger, Phys. Rev. 74, 373 (1948).

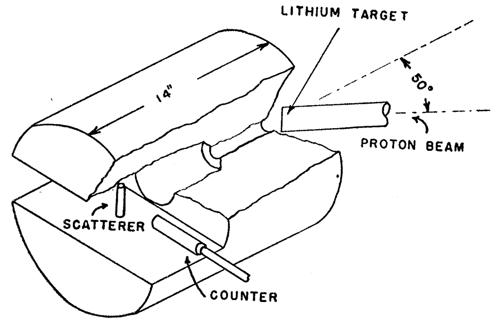

Fig. 2. Schematic view of experimental setup.

III. POLARIZATION OF NEUTRONS SCATTERED FROM HEAVY NUCLEI

The polarization of neutrons scattered from heavy nuclei was determined by measuring the left-right asymmetry in the scattering of 400-kev polarized neutrons under the same conditions as described in the preceding section. Scatterers of various materials which had been procured for another experiment[6] were available. All of the scatterers were cylinders 6.3 cm long. Table I lists the elements measured, the diameters of the samples, and the ratio of the diameter of the sample to the mean free path of the neutron in the sample. The choice of diameters chosen for the scatterers was influenced by three considerations; the diameter should not be greater than 2 cm in order to avoid an asymmetry which might be caused by the variation with angle of the neutron intensity from the Li(p,n) reaction, and hence a variation of flux across the scatterer; the diameter should not be greater than 80 percent of the mean free path to keep multiple scattering from becoming objectionably large; and, within the first two restrictions, the sample should be as large as possible in order to get a reasonably large counting rate.

Some of the nuclei will scatter both elastically and inelastically. If inelastic scattering with large degradation in energy were important, the ratio of the counting rates at the two different discriminator biases would be different, as at the lower bias inelastically scattered neutrons would be counted relatively more efficiently than at the higher discriminator bias. There seemed to be no evidence of such an effect. For each heavy element the counting rate at the low bias was about twice the rate at the high bias. For carbon and oxygen the ratio was higher than two to one, presumably because of the loss of energy in elastic scattering.

Measured left-right asymmetries for the different nuclei are listed in Table I, together with values corrected for multiple scattering. The multiple scattering corrections were made in the same manner as the corrections for scattering by oxygen. Both the

TABLE I. Sample parameters and experimental results.

Elements	Nuclear radius in cm $\times 10^{13}$	Sample diameter in cm	Diameter M.F.P.	Left-right scattering asymmetry	Left-right asymmetry corrected for multiple scattering	Polarization
Oxygen		1.35	0.79 0.275	1.92 ± 0.12	$2.52 \begin{smallmatrix} +0.35 \\ -0.25 \end{smallmatrix}$	-0.82
Carbon		1.9		1.000 ± 0.029		0
Cu	5.76	1.9	0.73	1.003 ± 0.023	1.003 ± 0.023	-0.003 ± 0.02
Zn	5.85	1.9	0.61	1.006 ± 0.025	1.005 ± 0.025	-0.006 ± 0.02
Zr	6.51	1.9	0.69	0.967 ± 0.022	0.954 ± 0.026	$+0.044 \pm 0.026$
Nb	6.56	1.7	0.72	0.894 ± 0.023	0.854 ± 0.032	$+0.148 \pm 0.031$
Mo	6.65	1.6	0.82	0.895 ± 0.027	0.850 ± 0.032	$+0.153 \pm 0.031$
Ag	6.89	1.8	0.79	0.920 ± 0.029	0.888 ± 0.031	$+0.112 \pm 0.033$
Cd	6.98	1.9	0.65	0.859 ± 0.039	0.817 ± 0.039	$+0.190 \pm 0.047$
Sn	7.10	1.9	0.49	0.866 ± 0.029	0.834 ± 0.034	$+0.174 \pm 0.034$
Ta	8.19	1.27	0.51	1.036 ± 0.038	1.045 ± 0.041	-0.038 ± 0.041
W	8.22	1.27	0.56	1.036 ± 0.033	1.040 ± 0.033	-0.037 ± 0.033
Bi	8.59	1.9	0.42	1.024 ± 0.023	1.027 ± 0.023	-0.025 ± 0.023

statistical standard error and an estimate of the multiple scattering error are included in the quoted uncertainty. Polarizations calculated from Eq. (1) are listed in the last column of Table I together with the probable error. In Fig. 3 these polarizations are plotted against the nuclear radius, taken as $1.45 \times 10^{-13} A^{\frac{1}{3}}$ cm.

IV. INTERPRETATIONS AND CONCLUSIONS

The elastic scattering of neutrons from nuclei can be described, in this energy region, as the result of two separate processes,[17] potential or body elastic scattering, and resonance or capture elastic scattering. Feshbach, Porter, and Weisskopf have pointed out that the resonance scattering is incoherent with body elastic scattering if the energy spread of the incident beam is sufficiently broad. It can be seen from the uncertainty principle that the interaction time is well defined for a scattering measurement made with a neutron beam which has a large energy spread. Therefore, scattering which results from the formation and decay of narrow long-lived compound states will interfere with neither the incident beam or the body elastic scattering. This condition should obtain for most of the elements measured as the neutron energy spread of 65 kev which was used should be much greater than the level widths. There may be small effects due to individual resonances, however, for the closed shell nuclei, zirconium, tin, and bismuth which are likely to form shorter-lived compound states. Polarization of scattered neutrons occurs through interference between scattering amplitudes of neutrons with their spins reversed and the amplitudes of neutrons whose spin directions were unchanged by the scattering interaction. Since compound elastic scattering will not, when averaged over resonances, interfere with the body elastic scattering, the polarization cannot be due to the effect of narrow resonances but must result from the body scattering or potential scattering itself.

The nuclear model of Feshbach *et al.*[1] explains the strongly varying patterns of average neutron cross sections in terms of the variations in the potential scattering. While this model of the nucleus will not account for polarization, the addition of a spin-orbit term to the potential well, as required by the shell model, will produce a polarization of the scattered neutrons. Calculations of the expected polarization were made using such a modification. The potential used was

$$V(r) = -V_0(1+i\zeta) - V'(\mathbf{l}\cdot\mathbf{s}),\ r<R$$
$$= 0,\ r>R,$$

where, from reference 1, $V_0 = 19$ Mev, $\zeta = 0.05$, and $R = 1.45 \times 10^{-13} A^{\frac{1}{3}}$ cm. Values of 1 and 2 Mev were chosen for V' in an attempt to fit the experimental polarization data.

Effects of neutrons of angular momentum greater than one were not considered in these calculations. These considerations do not take into account the spin of the scattering nucleus but describe the interaction of neutrons with the spinless nuclear core, and disregard the nucleons in the outer orbits which, according to the shell model, give the nucleus as a whole its spin. Consequently, the calculation is similar to that described previously[18] for a special case of neutrons scattered by a spinless nucleus. States of the neutron-nuclear core system are formed with a well-defined total angular momentum and scattered amplitudes are determined for S, $P_{\frac{1}{2}}$, and $P_{\frac{3}{2}}$ waves. The polarization is defined as $P = (A^*|\sigma_x|A)/d\sigma/d\omega$, where A is the body elastic scattering amplitude in the Y direction and $d\sigma/d\omega$, the differential cross section for scattering in the Y direction, is the sum of the body elastic scattering and the capture elastic scattering. The body elastic scattering intensity is just $|A|^2$. Although the total cross section for incoherent processes is determined by the potential, the division into capture elastic scattering and inelastic scattering, and the angular distributions of these processes must be estimated from other considerations. Polarizations were

[17] Feshbach, Porter, and Weisskopf (private communication).

[18] R. K. Adair, Phys. Rev. **86**, 155 (1952).

calculated under the assumption that the incoherent processes result entirely from capture elastic scattering, and that the angular distribution of these resonance-scattered neutrons is that characteristic of the decay of pure states, isotropic for $P_{\frac{1}{2}}$ and S waves, and of the form $1+3\cos^2\vartheta$ for $P_{\frac{3}{2}}$ neutrons. Coupling of the angular momentum with the nuclear spin will tend to make the $P_{\frac{3}{2}}$ distribution more nearly isotropic. Since the contribution of the capture scattering to the total scattering at this energy is not large, the uncertainties involved in these assumptions will not affect the calculated values of the polarization strongly.

Polarizations calculated in the manner described are shown by the solid and dashed lines in Fig. 3. There is qualitative similarity between the experimental values and the calculated curves. The position of the calculated curves as a function of the nuclear radius R is determined primarily by the value of V_0; a value of 18.5 Mev instead of 19 Mev would shift the whole curve towards higher values by about 0.1×10^{-13} cm and might give a better fit to the experimental points. While other small changes, notably an increase in the absorption coefficient, might also result in a better fit to the data, such changes may not be warranted by either the accuracy of the experiment or the reliability, as far as such detailed predictions are concerned, to be expected of so simple a description of the nucleus.

It appears that a value of V of about 40 Mev instead of 19 Mev may be more nearly correct.[19] All of the important scattering phase shifts are then increased almost exactly 360°, and there is very little difference in the physical scattering results. However, the values of V' deduced from these measurements must be multiplied by about $(40/19)^{\frac{1}{2}}$ if the deeper potential is correct.

The width of the resonance-like maxima and minima of the polarization curve increases with V'. While the magnitude of V' is not too well determined by the limited experimental data, a value larger than 2.5 Mev or smaller than 1.0 Mev would not appear to be in agreement with the measurements. It must be emphasized that since the value of V' is deduced primarily from measurements of nuclei of $A\approx100$, at energies and angles where only S and P waves are important, a value of 1–2 Mev for V' properly refers only to the interaction of P neutrons with nuclei having a mass of about 100. Calculations[20–22] concerning the value of the potential V' indicate that it may depend on the orbital angular momentum l and the nuclear radius R. Because of this it is difficult to compare the spin-

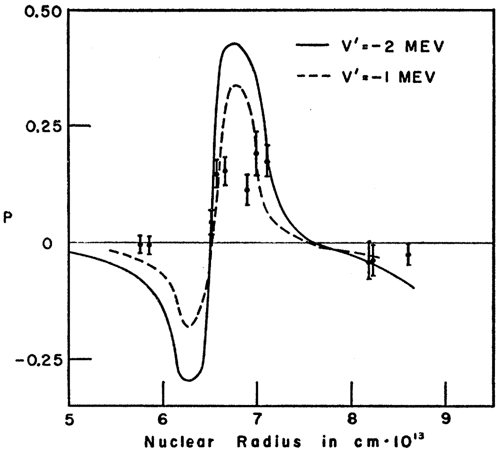

FIG. 3. The points show the measured polarizations of 400-kev neutrons produced by scattering from heavy nuclei as a function of nuclear radius, R. The solid curve shows values obtained when a potential term equal to -2 Mev ($\mathbf{l}\cdot\mathbf{s}$) is added to the potential used by Feshbach, Porter, and Weisskopf. The dashed curve represents the results of calculations for a spin-orbit term of -1 Mev ($\mathbf{l}\cdot\mathbf{s}$).

orbit energy indicated from these scattering measurements with that deduced from the shell model and the bound states of nuclei. However, a value of 1.5 Mev for V' in the scattering calculation would result in a splitting of about 2.25 Mev for a bound single P-wave nucleon outside of a closed shell, which is about what might be anticipated from the shell model.[21,23]

When plotted as a function of atomic weight, the experimental total cross sections at a neutron energy of 400 kev exhibit a resonance-like behavior in the region of atomic weights around 100. This general variation can be reproduced using the potential of Feshbach, Porter, and Weisskopf, where the rise in the cross section is attributed to a virtual P level. Total cross section calculations were made using S and P waves only, since the D-wave contribution is expected to be quite small at this energy. If no spin-orbit coupling is introduced, the predicted peak in the total cross section appears too high and narrow, while calculations which include a spin-orbit term -1.5 Mev ($\mathbf{l}\cdot\mathbf{s}$) in the potential are in fair agreement with the data in the neighborhood of the peak.

No detailed calculations concerning the effect of the spin orbit term on the angular distributions have been made.[5] Somewhat more isotropic angular distributions might be expected since terms in the angular distribution proportional to $P^{\pm1}(\cos\vartheta)$ will be introduced by spin-orbit coupling.

The basic ideas for this experiment were developed in the course of a conversation of one of the authors with Dr. C. K. Bockelman.

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[23] M. G. Mayer, Phys. Rev. **78**, 16 (1950).