# Neutron Depolarization on Scattering from Carbon, Paraffin, and Phosphorus*

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The depolarization of polarized thermal neutrons scattered from carbon, paraffin, and phosphorus has been measured. The results have been interpreted in terms of the spin flip probability on scattering, which for carbon was found to be equal to $-0.09\pm0.21$ and for hydrogen $0.56\pm0.10$, consistent with the theoretically expected values 0 and 0.65, respectively. For phosphorus, the measured spin flip probability of $0.73\pm0.15$ yields an incoherent scattering cross section of $3.7\pm0.8$b, of the same order of magnitude as the total scattering cross section (3.4b). This would imply one or more $s$-neutron resonance levels in phosphorus above 400 ev, the present upper limit of the well investigated part of the total neutron cross section of phosphorus.

## I. INTRODUCTION

IT follows from the assumption of spin-dependent nuclear forces that a slow neutron can change its spin orientation in a scattering process. It seemed to us to be of interest to demonstrate this effect directly. Furthermore, it was our intention to measure the effect qualitatively and thereby to open the possibility of another method of investigating certain features of the compound system.

The probability $Q$ of the spin flip depends on the spin $I$ of the nucleus and on its interaction with the neutron. The effect of this interaction is usually expressed in terms of the spin dependent scattering lengths $a_+$ and $a_-$ for the compound system of spin $I+\frac{1}{2}$ and $I-\frac{1}{2}$, respectively. In terms of these quantities, the total scattering cross section, $\sigma$, of a free nucleus for a slow neutron can be expressed as:[1]

$$\sigma=4\pi[(I+1)a_+^2+Ia_-^2]/(2I+1), \tag{1}$$

and the spin flip probability $Q$ is found to be:[1]

$$Q=\frac{2}{3}\frac{I(I+1)}{(2I+1)}\frac{(a_+-a_-)^2}{[(I+1)a_+^2+Ia_-^2]}. \tag{2}$$

It may be noted that the maximum value of $Q$ is $\frac{2}{3}$, independent of $I$. If the scattering nucleus is strongly bound, the scattering cross section must be multiplied by $[(A+1)/A]^2$, where $A$ is the atomic weight of the nucleus.[2] If more than one isotope is present in the scatterer, the formulas become more complicated.[1,3] In the present experiments only mono-isotopic scatterers were used.

The method which is described below is not the only one by means of which the change of neutron spin orientation can be observed. Indeed, in the crystalline scattering of neutrons one finds incoherent scattering[4] which may be due to isotope effects, temperature scattering, crystal imperfections, random distribution of nuclear spins, and neutron spin flip. In many cases it is possible to isolate the last two causes from the others[3] and, thus, to obtain $Q$; in fact calling this contribution to the incoherent scattering $\sigma_{\text{inc}}$, one can show that

$$Q=\tfrac{2}{3}(\sigma_{\text{inc}}/\sigma). \tag{3}$$

In a comparison of our method with crystal scattering, it may be noted that the two methods are fundamentally different as is shown, for example, by the fact that in the latter method crystalline material is essential for a determination of $\sigma_{\text{inc}}$, whereas this is not the case for a direct measurement of $Q$. As a matter of fact it will be argued later that appreciable crystalline interference is a disturbing factor for the direct determination of $Q$.

## II. METHOD

The present experiment is a direct method for the determination of the spin flip probability $Q$. After having checked the results in two cases ($C^{12}$ and $H^1$) where they were known from other experiments,[4] the method was also applied to the determination of the spin flip probability for an isotope not as yet investigated ($P^{31}$).

Instead of the depolarization of a beam of polarized slow neutrons as measured by $Q$ it is convenient to introduce the ratio $R(-1\leqslant R\leqslant 1)$ of the polarization[5] of the scattered beam of neutrons to that of the incident beam. It can be shown[1] that for single scattering

$$R=1-2Q. \tag{4}$$

For multiple scattering the relation between $R$ and $Q$ is much more complicated[6] and depends on the solution of a diffusion equation.

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† Now at Oregon State College, Corvallis, Oregon.
[1] O. Halpern and M. H. Johnson, Phys. Rev. **55**, 898 (1939).
[2] E. Fermi, Ricerca Sci. **7**, 13 (1936).
[3] For a review of the scattering theory and for references see E. O. Wollan and C. G. Shull, Phys. Rev. **73**, 830 (1948).
[4] Reference 3; and for later work C. G. Shull and E. O. Wollan, Naturwiss. **36**, 291 (1949); as well as data quoted in K. Way *et al.*, *Nuclear Data* (Nat. Bur. Standards Circ. No. 499, 1950).
[5] Polarization is defined as the ratio $(I_+-I_-)/(I_++I_-)$, where $I_+$ and $I_-$ are the intensities of the neutrons with the two possible spin orientations respectively.
[6] S. Borowitz and M. Hamermesh, Phys. Rev. **74**, 1285 (1948). Contrary to the opinion of these authors the depolarization-

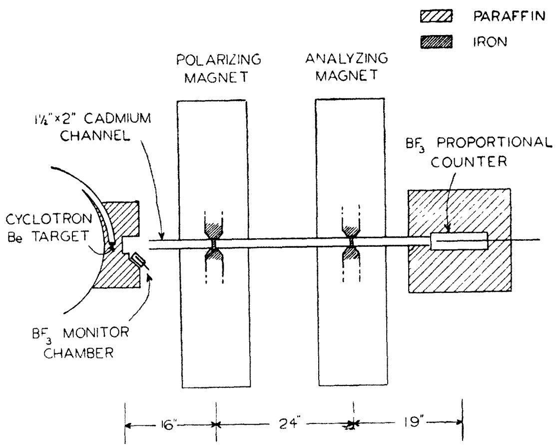


FIG. 1. The straight arrangement of polarizer and analyzer magnets.

Equation (4) shows that the single scattering experiment is very insensitive to small $Q(<0.05)$, and a diffusion type experiment is to be preferred in that case because the total spin flip probability increases with each collision of the neutron. However, for reasons of intensity and interpretation of results the width of the neutron beam should be greater than the thickness of the scatterer (5 to 10 mean free paths). Since such a wide neutron beam was not available to us, we performed a single scattering experiment.

It should be mentioned here that this type of depolarization experiment was first suggested by Schwinger and Rabi[7] who calculated $R$ [Eq. (4)] for hydrogen and

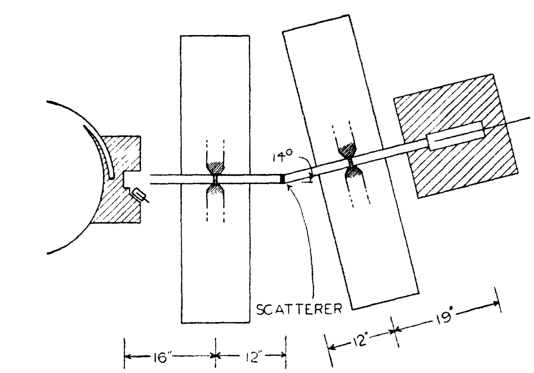


FIG. 2. The oblique arrangement of polarizer and analyzer magnets. The symbolism is the same as for Fig. 1.

diffusion experiment seems to be quite feasible with the broad neutron beams available from piles. Indeed, for a nonabsorbing scatterer of 10 mean free path thickness the fractional transmitted intensity in the forward direction is approximately $0.3\omega_d/4\pi$, where $\omega_d$ is the solid angle intercepted by the detector. Similar conditions are encountered in the present experiment, but the available neutron beam was not broad enough to perform a diffusion type experiment. Figure 3 in the above paper is not labeled correctly and should be either $\Delta_0(10)$ *vs* $\alpha$ or $\sigma(10)$ *vs* $\beta$. This would bring the calculations into rather close agreement with those of Halpern. See O. Halpern, Phys. Rev. **75**, 1633 (1949); and O. Halpern and R. K. Luneberg, Phys. Rev. **76**, 811 (1949).

[7] J. Schwinger and I. Rabi, Phys. Rev. **51**, 1003 (1937).

pointed out that a measurement of $R$ for neutron scattering by hydrogen atoms would easily demonstrate the nature of the excited state of the deuteron. The results of the present experiment are in agreement with their calculations for a virtual state.

Our experimental method follows rather closely that described in previous papers[8,9] and the reader is referred to these for details. Only such information is repeated here as is necessary for the understanding of the experiment.

The neutrons used in the experiment were produced by a Be($d$,$n$) reaction in the Stanford cyclotron ($2\frac{1}{2}$-Mev deuterons) and thermalized in a paraffin moderator. The neutrons were partially polarized by passage through iron blocks[10] magnetized close to saturation. The detailed theory of the polarization has been studied by Halpern and Holstein[11] and has been adequately verified.[9,12] However, except for a correction factor discussed below, our experiment is independent of the theory of the polarizing effect. Our apparatus[13] consisted of a "polarizer" magnet and an "analyzer" magnet which provided magnetic fields of the order of 12,000 oersteds in two identical hot rolled steel blocks, $1\frac{1}{2}$ in. $\times 2$ in. in cross section and $\frac{1}{2}$ in. thick in the direction of the neutron beam. The neutron beam was channeled in rectangular cadmium channels, also $1\frac{1}{2}$ in.$\times 2$ in. in cross section. We made measurements both with the straight arrangement shown in Fig. 1, when no scatterer was used, and with the oblique arrangement shown in Fig. 2, when a scatterer was inserted. The reasons for these arrangements are discussed in Sec. IIIA.

We shall now analyze briefly the experiments necessary to determine the polarization ratio $R$ [Eq. (4)], using the above arrangements. Considering the straight arrangement (Fig. 1) first, let $f(\tau)d\tau$ be the number of neutrons with inverse velocities (usually expressed in $\mu$sec/meter) between $\tau$ and $\tau+d\tau$, which are recorded in the detection chamber per unit time after having passed the polarizer and analyzer iron blocks, both unmagnetized. If either one or both of the iron blocks are magnetized, the number of neutrons recorded will increase by a factor $C(\tau)$, which we denote as follows:

(a) polarizer and analyzer both magnetized:

$$C(\tau)=C_D(\tau);$$

(b) polarizer magnetized, analyzer unmagnetized:

$$C(\tau)=C_P(\tau);$$

(c) analyzer magnetized, polarizer unmagnetized:

$$C(\tau)=C_A(\tau);$$

[8] Bloch, Nicodemus, and Staub, Phys. Rev. **74**, 1025 (1948).
[9] Fleeman, Nicodemus, and Staub, Phys. Rev. **76**, 1774 (1949).
[10] F. Bloch, Phys. Rev. **50**, 259 (1936); **51**, 994 (1937).
[11] O. Halpern and T. Holstein, Phys. Rev. **59**, 960 (1941).
[12] Hughes, Wallace, and Hotzman, Phys. Rev. **73**, 1277 (1948).
[13] All the apparatus used in this experiment had been constructed previously under the direction of Professor H. H. Staub, now at the University of Zurich, Switzerland.

(d) polarizer and analyzer both unmagnetized:

$$C(\tau)=1.$$

The total recorded intensities corresponding to these four cases are:

$$I_D=\int C_D(\tau)f(\tau)d\tau, \tag{5a}$$

$$I_P=\int C_P(\tau)f(\tau)d\tau, \tag{5b}$$

$$I_A=\int C_A(\tau)f(\tau)d\tau, \tag{5c}$$

$$I_0=\int f(\tau)d\tau, \tag{5d}$$

where the integration is assumed to extend only over inverse velocities of neutrons absorbed in cadmium ($C$-neutrons) (Sec. IIIA and B). By means of these measured quantities one can conveniently define the "double transmission effect" $\eta_D$:

$$\eta_D=\frac{I_D-I_0}{I_0}=\frac{\int(C_D-1)fd\tau}{\int fd\tau}; \tag{6a}$$

the "single transmission effect, polarizer on," $\eta_P$:

$$\eta_P=\frac{I_P-I_0}{I_0}=\frac{\int(C_P-1)fd\tau}{\int fd\tau}; \tag{6b}$$

and the "single transmission effect, analyzer on," $\eta_A$:

$$\eta_A=\frac{I_A-I_0}{I_0}=\frac{\int(C_A-1)fd\tau}{\int fd\tau}. \tag{6c}$$

Considering next the oblique arrangement of Fig. 2, we note that the scattered intensity $I_0^*$, recorded when both the polarizer and the analyzer iron blocks are unmagnetized, is:

$$I_0^*=\int k(\tau)f(\tau)d\tau, \tag{7}$$

where $k(\tau)$ is a factor which depends on the solid angle $\omega_d$, which the detector subtends at the scatterer on the absorption cross section $\sigma_a$ and on the scattering cross section $\sigma$ [Eq. (1)], of the scatterer. Although $k(\tau)$ can be determined completely experimentally by a velocity selection method (see Appendix), it is not difficult to show that for isotropic scattering in the forward direction from a thin scatterer:[14]

$$k(\tau)=[(A+1)/A]^2\sigma nd\exp(-\sigma_a nd)r\omega_d/4\pi. \tag{8}$$

Here $n$ is the number of scattering atoms per unit volume, $d$ is the thickness of the scatterer, and $r$ is the ratio of the solid angle subtended by the scatterer to that subtended by the detector at the neutron source in the straight arrangement (Fig. 1). By thin scatterer is meant here that $n\sigma d\ll 1$.

In the presence of crystalline interference the form of $k(\tau)$ may be altered radically[14,15] and may depend not only on the previously mentioned quantities, but also on crystallite size and structure, angle of scattering, and temperature. For the present experiment it is imperative that crystalline interference be negligible if the formulas given below are used, because it is assumed implicitly in the derivation that the coherently and incoherently scattered neutron intensities are reduced by the same factor $k(\tau)$.

When both the polarizer and the analyzer iron blocks are magnetized in the oblique arrangement (Fig. 2), it can be shown[16] that the scattered neutron intensity $I_D^*$ recorded is:

$$I_D^*=R\int C_D(\tau)k(\tau)f(\tau)d\tau+(1-R)\int C_P(\tau)C_A(\tau)k(\tau)f(\tau)d\tau. \tag{9}$$

$R$ is the ratio of the polarization of the scattered neutrons to that of the incident neutrons and is the quantity which we wish to determine [see Eq. (4)].[17] It may be of interest to point out that the first term of the expression for $I_D^*$ corresponds to those neutrons which have not changed their spin orientation on scattering, while the second term corresponds to those that have undergone spin flip. At this point it can be seen that the assumption of equal values of $k(\tau)$ for both terms implies the absence of crystalline interference.

Equation (9) can be rewritten in a more convenient form by using the fact[8] that $C_P$ and $C_A$ are close to unity (1.04 in our experiment), so that $C_PC_A\cong C_P+C_A-1$:

$$I_D^*=R\int C_Dkfd\tau+(1-R)\int C_Pkfd\tau+(1-R)\int C_Akfd\tau.$$

[14] Equation (8) does not take into account temperature scattering. See, for example, R. Weinstock, Phys. Rev. **65**, 1 (1944).

[15] Halpern, Hamermesh, and Johnson, Phys. Rev. **59**, 981 (1941).

[16] Equation (9) is analogous to Eq. (4) of reference 8. In order to derive this equation it is necessary to consider the neutrons with different spin orientations separately.

[17] It may be noted that in the single scattering experiment $R$ is independent of the neutron velocity, whereas in the diffusion type experiment it will depend on the neutron velocity unless absorption is negligible.

Defining $\eta_D^*$ as "double transmission effect on scattering" similar to Eq. (6a), we obtain with the help of Eq. (7):

$$\eta_D^*=\frac{I_D^*-I_0^*}{I_0^*}=R\frac{\int(C_D-1)kfd\tau}{\int kfd\tau}+(1-R)\left\{\frac{\int(C_P-1)kfd\tau}{\int kfd\tau}+\frac{\int(C_A-1)kfd\tau}{\int kfd\tau}\right\}. \quad (10)$$

The fractions containing the integrals resemble the transmission effects defined in Eqs. (6a–6c), except for the factor $k$ appearing in the integrals. It is shown in the Appendix that by defining a "hardening factor," $H$, in general not very different from unity,

$$H=\left(\int p^2fd\tau\Big/\int fd\tau\right)\Big/\left(\int p^2kfd\tau\Big/\int kfd\tau\right), \quad (11)$$

where $p$ is the polarization cross section of iron,[10,18] Eq. (10) can be rewritten as

$$\eta_D^*=(1/H)[R\eta_D+(1-R)(\eta_P+\eta_A)].$$

From this equation we obtain the polarization ratio $R$:

$$R=[H\eta_D^*-(\eta_P+\eta_A)]/[\eta_D-(\eta_P+\eta_A)] \quad (12)$$

and the spin flip probability, by inserting this value of $R$ into Eq. (4):

$$Q=(\eta_D-H\eta_D^*)/2[\eta_D-(\eta_P+\eta_A)]. \quad (12a)$$

This determination of the spin flip probability rests, therefore, on the experimental determination of the quantities $\eta_D$, $\eta_P$, $\eta_A$, $\eta_D^*$, and the theory of neutron polarization by magnetized iron[11] is needed only to calculate the correction factor, $H$, usually not very different from unity.

## III. MEASUREMENTS AND RESULTS

### (A) Preliminary Considerations

In the production of polarized neutrons by passage through magnetized iron, a compromise must always be made between the increase in polarization and the decrease in intensity as the thickness of the iron blocks is increased. Taking account of these factors as well as of the expected background, consisting mostly of neutrons not captured by cadmium, we found $\frac{1}{2}$ in. to be the best thickness for both the polarizer and the analyzer iron blocks.

Inspection of the expressions for the various intensities which have to be measured [Eqs. (5), (7), and (9)] shows that the critical measurement is that of the difference between the scattered intensities $I_D^*$ and $I_0^*$. In fact the scattered intensities are severely reduced by the factor $k$ which is proportional to the fractional solid angle $\omega_d/4\pi$ subtended by the detector at the scatterer [Eq. (8)]. $\omega_d$ cannot be made arbitrarily large because the dimensions of the polarizer and analyzer magnets, necessary to produce a saturation field, prescribe a minimum distance between the scatterer and the detector which was about 30 in. in our case (see Fig. 2). If it were not for this practical limitation, considerably larger solid angles could have been used, limited only by the distance necessary to avoid neutrons which are diffusely scattered in the iron blocks. These neutrons render the blocks less effective. By separate measurements we have shown that the full effectiveness is obtained at distances larger than 6 in. from the analyzer. While our actual distance certainly satisfied this requirement, it disadvantageously reduced the solid angle to $\omega_d/4\pi\cong3\times10^{-4}$. Also, we measured for the solid angle ratio $r$, appearing in Eq. (8), $r\cong4.1$.

Connected with these considerations is that of the angle of scattering in the oblique arrangement (Fig. 2). It is desirable to make this angle as small as possible, because a small scattering angle avoids crystalline interference (Sec. IIIC). But here again one is limited by the consideration that no direct neutrons from the polarizer must strike the analyzer iron block in order to insure that all neutrons passing through the analyzer indeed come from the scatterer. In view of these considerations, we have chosen a scattering angle of 14°.

Measurements of the slow neutron intensity scattered from paraffin (0.3 cm thick) yielded approximately 100 cpm with the cyclotron running at maximum beam current (20 $\mu$amp). The fast neutron intensity was about 4 times larger, convincing us that a rough velocity selection method was necessary in order to reduce the fast neutron background. Consideration of the neutron velocity spectrum[9] and actual measurements indicated that the following type of pulsing cycle, repeated at a rate of 500 cps, would be advantageous:

0–880 $\mu$sec: cyclotron on, detector off;
1180–1980 $\mu$sec: cyclotron off, detector on;
remaining time: cyclotron and detector off.

The pulsing equipment is described in reference 9. With an average cyclotron beam current of 10 $\mu$amp this pulsing yielded approximately 50 slow neutrons/min scattered from paraffin and recorded by the detector above an epithermal background of 15 cpm. These numbers were considered encouraging enough to warrant the attempt of the main experiment.

### (B) Measurements with the Straight Arrangement

A determination of the spin flip probability [Eq. (12a)] requires, first, a knowledge of the "straight"

[18] J. Steinberger and G. C. Wick, Phys. Rev. 74, 1207 (1948).

single- and double-transmission effects $\eta_P$, $\eta_A$, and $\eta_D$, which are, of course, independent of the scatterer. These effects were measured as described in reference 9, leaving both polarizer and analyzer iron blocks in place during all measurements as in reference 8. The neutron intensity was monitored by an integrating boron trifluoride chamber[19] which caused the appropriate polarizing magnets to be alternately switched on and off.[9] Any transmission effect is then given by:

$$\eta=(N'-N)/(N-N_{\mathrm{Cd}}), \tag{13}$$

where $N'$, $N$, and $N_{\mathrm{Cd}}$ are the total number of counts for an equal number of monitor intervals with the appropriate magnets on, the magnets off, and with a cadmium shield in front of the cadmium channel (Fig. 1), respectively.

All measurements were checked for statistical consistency and were repeated several times throughout the course of the experiment. About 200 monitor intervals (each of approximately 2-min duration), totaled for each of the numbers in Eq. (13), yielded the following values:

$$\begin{aligned}\eta_A&=\ 4.20\pm0.19 \text{ percent},\\ \eta_P&=\ 4.24\pm0.15 \text{ percent},\\ \eta_D&=14.67\pm0.13 \text{ percent}.\end{aligned} \tag{14}$$

These transmission effects are larger than those found by Fleeman, Nicodemus, and Staub[9] for similar thicknesses of iron, because the pulsing used here accentuates the low energy part of the slow neutron spectrum (Fig. 3) with a resulting increase in the effective polarization cross section.[18]

### (C) Measurements with the Oblique Arrangement—Carbon

According to Eq. (2) a scatterer with spin equal to zero should not depolarize the neutron beam [$Q=0$ and $R=1$, Eq. (4)]. To check this point we scattered polarized neutrons from graphite, since it has a very low absorption cross section and a reasonable scattering mean free path for thermal neutrons (2.7 cm for our graphite).

In order to obtain enough scattered intensity we used a scatterer of 2.5 cm thickness. Under these conditions double scattering takes place to some extent, but the disturbing effect on our results is negligible compared to our statistical error.

As was mentioned in Sec. II, crystalline interference is to be avoided in this experiment. This can be achieved by observing the scattering under small angles and by rejecting neutrons below the long wavelength Bragg cutoff through pulsing. Under these conditions one observes only incoherent scattering,[20] and, furthermore, the Bragg cutoff occurs at small neutron inverse velocities with the advantage that the major part of the available neutron spectrum can be used. Indeed, calling $\tau_B$ the neutron inverse velocity corresponding to the Bragg cutoff:

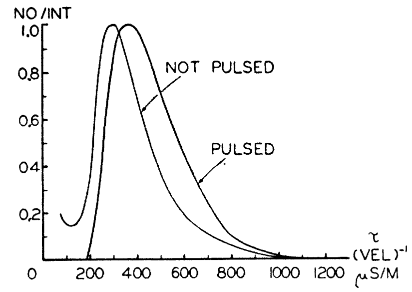


FIG. 3. The effect of cyclotron pulsing on the detected neutron spectrum. The maxima of both curves have been arbitrarily normalized to unity.

$$(h/m)\tau_B=2d_{\max}\sin\theta, \tag{15}$$

where $h$ is Planck's constant, $m$ the mass of a neutron, $d_{\max}$ the maximum interplanar distance in the polycrystal, and $\theta$ the glancing angle between the neutron beam and the crystal plane with $d_{\max}$ (here, $\theta=7°$). For graphite[21] $d_{\max}=6.69$A, so that $\tau_B=420$ $\mu$sec/m.

For reasons of intensity we were not able to use a system of pulsing which would have eliminated all coherent scattering. Inspection of Figs. 3 and 5 shows that roughly only one-half of the neutrons were scattered incoherently under our conditions. However, this does not invalidate our final conclusions for carbon below, because for $Q=0$ the distinction between coherent and incoherent scattering is immaterial in our experiment.

The final result of 300 monitor intervals each for the numbers in Eq. (13) yielded for the double-transmission effect on scattering from graphite:

$$\eta_D^*=13.6\pm2.2 \text{ percent}.$$

The error indicated is the standard deviation. Calculation of the hardening factor (see Appendix) gave $H=1.16$, so that Eqs. (12a) and (14) yield

$$\boldsymbol{Q=-0.09\pm0.21} \quad \textbf{(Carbon)}. \tag{16}$$

This result is consistent with the theoretical result $Q=0$ [Eq. (2)] expected for a scattering nucleus with zero spin. It is also in agreement with the fact that carbon has no measurable spin incoherent scattering.[3]

### (D) Measurements with the Oblique Arrangement—Hydrogen

We measured the spin flip probability for hydrogen, because it had been investigated by other methods[22,23] and, thus, allowed us to establish a check for our

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[19] E. M. Fryer and H. Staub, Rev. Sci. Instr. **13**, 187 (1942).
[20] E. Fermi and L. Marshall, Phys. Rev. **72**, 408 (1948).
[21] *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Company, Cleveland, 1941).
[22] Sutton, Hull, Anderson, Bridge, De Wire, Lavatelli, Long, Snyder, and Williams, Phys. Rev. **72**, 1147 (1947).
[23] Shull, Wollan, Morton, and Davidson, Phys. Rev. **73**, 842 (1948).

method. Since hydrogen is the predominant scatterer in paraffin, we used a paraffin scatterer. This has the additional advantage that the scattering cross section of the hydrogen nuclei is increased by the chemical binding effect[2] of the atoms, necessitating only a thin scatterer for our experiment.

In order to determine the maximum thickness of paraffin at which single scattering is still predominant, we measured the intensity of the scattered $C$-neutrons [$I_0^*$, Eq. (7)] as a function of the paraffin thickness (Fig. 4). It can be seen from Fig. 4 that 0.3 cm is still a suitable thickness, since single scattering is predominant as long as a linear relation exists between the scattered intensity and the thickness.

Using a paraffin scatterer 0.31 cm thick, we obtained for the double-transmission effect on scattering:

$$\eta_D^* = 7.9 \pm 1.1 \text{ percent},$$

after measuring 200 monitor intervals for each of the numbers of Eq. (13). Consideration of the hardening factor for paraffin (see Appendix) shows that in our case $H \cong 1.00$, so that Eqs. (12) and (14) give for the the polarization ratio:

$$R = -0.08_5 \pm 0.18. \tag{17}$$

Since the carbon atoms contribute slightly to the scattering from paraffin, a small correction must be applied to Eq. (17) in order to obtain the polarization ratio for hydrogen, $R_{\mathrm{H}}$. If $R_{\mathrm{C}}$ represents the polarization ratio for the carbon atoms and $\langle \sigma'_{\mathrm{H}} \rangle_{\mathrm{Av}}$ and $\langle \sigma'_{\mathrm{C}} \rangle_{\mathrm{Av}}$ are the average differential scattering cross sections in the forward direction for the hydrogen and carbon atoms respectively, it is easily seen that for single scattering:

$$R = (46\langle \sigma'_{\mathrm{H}} \rangle_{\mathrm{Av}} R_{\mathrm{H}} + 22\langle \sigma'_{\mathrm{C}} \rangle_{\mathrm{Av}} R_{\mathrm{C}}) / (46\langle \sigma'_{\mathrm{H}} \rangle_{\mathrm{Av}} + 22\langle \sigma'_{\mathrm{C}} \rangle_{\mathrm{Av}}), \tag{18}$$

where we have assumed the chemical formula of paraffin to be $C_{22}H_{46}$. Since $R_{\mathrm{C}} = 1$ [Eq. (16)], $\langle \sigma'_{\mathrm{H}} \rangle_{\mathrm{Av}} = 81/(4\pi)$ b/sterad[24] and $\langle \sigma'_{\mathrm{C}} \rangle_{\mathrm{Av}} = 5.2/(4\pi)$ b/sterad[3] in the forward scattering direction, we obtain from Eqs. (17) and (18) $R_{\mathrm{H}} = -0.11 \pm 0.19$ and, hence, from Eq. (4) for the spin flip probability:

$$Q = \mathbf{0.56 \pm 0.10} \quad \textbf{(Hydrogen)}.$$

This result is consistent with the value $Q = 0.650 \pm 0.005$, obtained by substituting the free coherent and total scattering cross sections ($\sigma_{\mathrm{coh}} = 0.50 \pm 0.075$b[4] and $\sigma = 20.36 \pm 0.10$b[24]) into Eq. (3) for $Q$. The agreement shows, together with the previously mentioned result on carbon, that our arrangement was equally capable of detecting the presence or absence of depolarization in the scattering of neutrons.

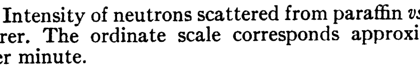


FIG. 4. Intensity of neutrons scattered from paraffin *vs* thickness of scatterer. The ordinate scale corresponds approximately to counts per minute.

### (E) Measurements with the Oblique Arrangement—Phosphorus

Having, thus, demonstrated the applicability of our method, we have likewise applied it to the scattering of polarized neutrons from white phosphorus, the only one of the easily available mono-isotopic elements with nonzero spin which had not been investigated[25] by other methods.[4] Red phosphorus cannot be used for this experiment because it contains various amounts of adsorbed water depending on its age and method of preparation. Our phosphorus sample was melted into a brass box (0.010-in. wall thickness) approximately 5.4 cm long and fitting into the knee of the cadmium channel (see Fig. 2). The scattering mean free path in white phosphorus is 8.5 cm and, the scattered $C$-neutron intensity was only about 10 cpm. Seven hundred monitor intervals for each of the quantities entering into Eq. (15) yielded for the double-transmission effect on scattering:

$$\eta_D^* = 5.2 \pm 1.6 \text{ percent}.$$

The hardening factor was calculated to be $H = 1.13$ (see Appendix), and since the scattered neutrons showed no crystalline interference (Fig. 7), we can substitute into Eq. (12) to obtain the polarization ratio $R = -0.40 \pm 0.29$. Correction for the neutrons scattered from the brass container[26] (about 4 percent of the total scattered intensity) changes this number to $-0.46 \pm 0.30$ and gives for the spin flip probability [Eq. (4)]:

$$Q = \mathbf{0.73 \pm 0.15} \quad \textbf{(Phosphorus)}.$$

This result together with the value[27] 3.4b for the free

[24] Calculated from the free proton scattering cross section of 20.36b [E. Melkonian, Phys. Rev. **76**, 1744 (1949)]. The reason for using the bound scattering cross section comes from a consideration of center of mass effects. See, for example, L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 105.

[25] We believe that this is due to a general reluctance to handle white phosphorus. Although due precautions must be taken not to touch the material, it can be melted under water at approximately 50°C and can then easily be poured (also under water) from one container to another. If copper sulfate is added to the water, the copper will plate out on the phosphorus and will protect it from oxidation when it is exposed to air. (We want to thank Professor Eric Hutchinson of the Chemistry Department, Stanford University, for having given us this valuable information.)

[26] Cu and Zn scatter predominantly coherently (reference 4) The correction follows from an expression similar to Eq. (18).

[27] "Columbia velocity selector," unpublished, quoted by R. K. Adair, Revs. Modern Phys. **22**, 249 (1950). Our own results would favor a value near 3.8b, while Hibdon and Muehlhause [Phys. Rev. **76**, 100 (1949)] give 4.1b.

TABLE I. Scattering data for isotopes with $I\neq 0$.[a]

| Isotope | Spin $I$ | Free total scattering cross section $\sigma$ (barns) | Spin incoherent scattering cross section, $\sigma_{\text{inc}}$ (barns) | Spin flip probability $Q$ [Eq. (3)] | Prominent $s$-neutron scattering resonance[b] | Remarks |
|---|---|---|---|---|---|---|
| $H^1$ | 1/2 | 20.36 | 19.86 | 0.650 | | Virtual state of $H^2$. |
| $H^2$ | 1 | 3.3 | 1.1 | 0.22 | ? | |
| $Li^7$ | 3/2 | $\sim$1.5 | $\sim$0.9 | $\sim$0.4 | 1.15 Mev[c] | |
| $Be^9$ | 3/2 | 6.1 | 0 | 0 | | No $s$-res. <1.5 Mev. |
| $N^{14}$ | 1 | 9.96[d] | 6.0 | 0.4 | ? | 2–150 kev not investigated; res. >500 kev. |
| $F^{19}$ | 1/2 | $\sim$3.6 | $\sim$0.5 | $\sim$0.09 | | 0.3–10 kev not investigated; res. >30 kev. |
| $Na^{23}$ | 3/2 | 3.2 | 1.8 | 0.37 | 3 kev | |
| $Al^{27}$ | 5/2 | 1.4 | 0 | 0 | | No res. <40 kev. |
| $P^{31}$ | 1/2 | 3.4 | $\geqslant$2.9[e] | $\geqslant$0.58[f] | ? | No res. <0.4 kev; not well investigated >0.4 kev. |
| $V^{51}$ | 7/2 | 5 | >4.9 | >0.65[f] | $\sim$2.7 kev | |
| $Mn^{55}$ | 5/2 | 2.2 | 0.9 | 0.27 | 0.345, 2.4 kev | |
| $Co^{59}$ | 7/2 | $\sim$5 | $\sim$3 | $\sim$0.4 | 115 ev | |
| $As^{75}$ | 3/2 | $\sim$7 | $\sim$2 | $\sim$0.2 | $10^2$–$10^3$ ev | |
| $Nb^{93}$ | 9/2 | 6.2 | $\sim$0.2 | $\sim$0.02 | | No res. <0.4 kev; not investigated >0.4 kev. |
| $I^{127}$ | 5/2 | 3.8 | 0.4 | 0.07 | 20–40 ev | |
| $Ta^{181}$ | 7/2 | 7.0 | 0.9 | 0.09 | 4.0 ev | |
| $Au^{197}$ | 3/2 | $\sim$9 | $\sim$1.5 | $\sim$0.1 | 4.8, >345 ev | |
| $Bi^{209}$ | 9/2 | $\sim$10 | $\sim$0 | $\sim$0 | | No res. <1.5 Mev. |

[a] Except where otherwise mentioned, the spin and cross section data are taken from K. Way *et al.*, *Nuclear Data* (Nat. Bur. Standards Circ. No. 499, 1950).
[b] Except where otherwise mentioned, the resonance scattering energies are taken from Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950); and from R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[c] R. K. Adair, Phys. Rev. **79**, 1018 (1950).
[d] E. Melkonian, Phys. Rev. **76**, 1750 (1949).
[e] Present paper.
[f] Maximum value of $Q$ is $\frac{2}{3}$.

total scattering cross section of phosphorus would yield a spin incoherent scattering cross section [Eq. (3)]:

$$\sigma_{\text{inc}}=\mathbf{3.7\pm0.8b},$$

or a coherent cross section of less than 0.5b.

## IV. DISCUSSION

Other isotopes with non-zero spin for which $\sigma$ and $\sigma_{\text{inc}}$ are known[4] are listed in Table I. Calculations[28–32] using the Breit-Wigner formula[33] for resonance and potential scattering indicate that large spin incoherent scattering (or large spin flip probability) in these cases can be accounted for, at least in part, by one or more prominent $s$-neutron scattering resonances. These resonances are given in Table I.

Inspection of the available data on the total neutron cross section of phosphorus[27] shows no neutron resonances, but this is not too remarkable since the cross section has been measured with good energy resolution only between 0.02 and 400 ev. As in every well investigated light isotope, one might expect neutron resonances in the range of 0.05 to 3 Mev. Such resonances have been found recently[34] in the $P^{31}(n,p)$ cross section in the range of neutron energies from 1.9 to 3.8 Mev. However, in addition to these resonances our result of a large spin flip probability for phosphorus strongly suggests one or more prominent $s$-neutron scattering resonances even closer to the thermal region than 0.05 Mev. Indeed, we believe that the case of $P^{31}$ may be similar to that of $Na^{23}$, which shows[35] a rather unsuspected scattering resonance at about 3000 ev, but our available means do not permit us to test this point.

The authors wish to thank Professor F. Bloch for the many stimulating discussions and encouragement during the course of this experiment. They also wish to thank Mr. H. Roderick for the preparation of the phosphorus scatterer and for the assistance in taking some of the data.

## APPENDIX

We first wish to show that an expression in Eq. (10) of the form

$$\left[\int (C-1)kfd\tau\right]\Big/\left[\int kfd\tau\right] \tag{19}$$

can be written as

$$\left[\int (C-1)fd\tau\right]\Big/\left[\bar{H}\int fd\tau\right], \tag{20}$$

where $\bar{H}$ is given by Eq. (11), independently of whether $C=C_A$, $C_P$, or $C_D$. Calling the thickness of the iron blocks magnetized in a particular experiment $d_m$, the theory of the polarizing effect[11] gives for $C-1$:

$$C-1\cong\tfrac{1}{2}n^2p^2d_m{}^2F. \tag{21}$$

$n$ is the number of Fe atoms per cm$^3$, $p$ is the polarization cross

[28] M. Hamermesh and C. O. Muehlhause, Phys. Rev. **78**, 175 (1950).
[29] C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **79**, 44 (1950). This particular calculation may be somewhat inaccurate if the potential scattering of $Cl^{35}$ or $Cl^{37}$ is spin dependent.
[30] C. O. Muehlhause, Phys. Rev. **79**, 1002 (1950).
[31] R. K. Adair, Phys. Rev. **79**, 1018 (1950).
[32] W. Selove, Phys. Rev. **80**, 290 (1950).
[33] H. A. Bethe, Revs. Modern Phys. **9**, 69 (1937).
[34] E. Luescher *et al.*, Helv. Phys. Acta **23**, 561 (1950).
[35] Hibdon, Muelhause, Selove, and Woolf, Phys. Rev. **77**, 730 (1950).

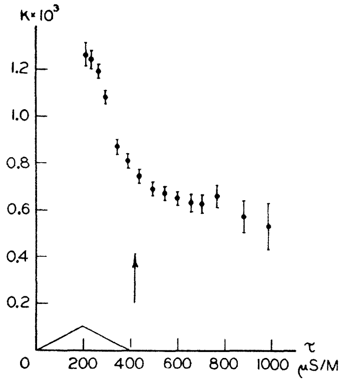


FIG. 5. The scattering factor $k(\tau)$ for the graphite scatterer. The arrow indicates the calculated position of the long wavelength Bragg cutoff. The resolution triangle is also shown.

section, and $F$ is a function about which we need to know only that it depends on $d_m$ and that it is velocity independent. Equation (21) assumes $npd_m \ll 1$, which is fulfilled to a sufficient degree in our case. Substitution of Eq. (21) into Eq. (19) shows that the velocity-independent factor $\frac{1}{2}n^2d_m^2F$ cancels out, thus, establishing Eq. (20), independent of $d_m$.

In the calculation of the hardening factors [Eq. (11)] we have used plots of $f$ and $p^2f$ made by Professor Staub for reference 9. The scattering factor $k$ was obtained for each scatterer by measuring the velocity spectrum of the scattered neutrons and comparing it to the direct spectrum from the howitzer. The iron blocks were removed for this measurement in order to gain intensity, and the inverse velocity resolution was made rather poor (200 $\mu$sec/m half-width) for the same reason.

Figure 5 shows $k$ for the graphite scatterer. The drop around 300 to 400 $\mu$sec/m corresponds to the long wavelength Bragg cutoff expected at 420 $\mu$sec/m but broadened by the inverse velocity resolution.[36] In the calculation of $H$ we have not corrected for this broadening, since it would not affect the accuracy of our results.

Figure 6 shows $k$ for paraffin. Since the scattering cross section is proportional[2] to $\mu^2$ and since the number of neutrons scattered in the *forward direction* into the detector is proportional[37] to $1/\mu^2$, where $\mu$ is the reduced mass of the neutron in terms of the neutron mass, $k$ is expected to be practically velocity independent. At a scattering angle of 14° the calculated variation of $k$ in our range of neutron velocities (Fig. 3) is only $2\frac{1}{2}$ percent and, therefore, we have assumed $H=1.00$ in the calculation of Eq. (17).

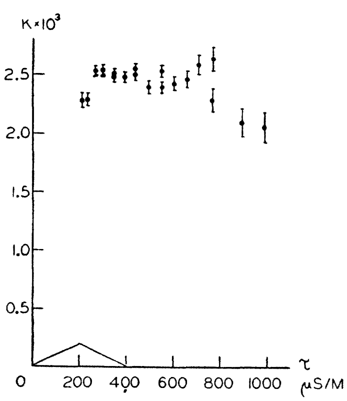


FIG. 6. The scattering factor $k(\tau)$ for the paraffin scatterer. At some neutron inverse velocities two independent measurements of the direct and scattered neutron spectra were made.

[36] The shape of this curve is quite similar to that taken for lead by R. Latham and J. M. Cassels, Nature **161**, 282 (1948).

Figure 7 shows $k$ for the phosphorus scatterer. The absence of a noticeable Bragg cutoff, expected around 460 $\mu$sec/m corresponding to a lattice spacing[38] of 7.17A, shows the absence of any appreciable crystalline interference. This is consistent with the very diffuse scattering of x-rays at room temperature[38] and also with the large spin flip probability found in this experiment. If we assume that the decrease in scattered intensity with increasing inverse velocity is caused only by absorption in the phosphorus (the brass container contributes less than 6 percent to the absorption), the shape of the curve of Fig. 7 should follow Eq. (8). Comparison with this equation yields an absorption cross section many times laiger than the values of[39] 0.15 to[40] 0.3b quoted in the literature.

Subsequent experiments have shown that the total *direct transmission* cross section of our phosphorus sample is consistent

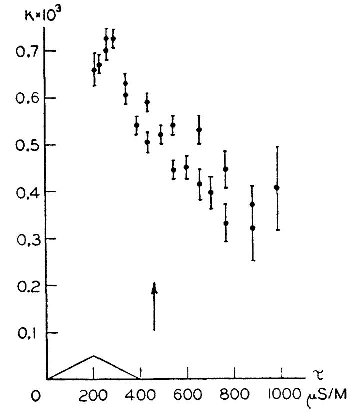


FIG. 7. The scattering factor $k(\tau)$ for the phosphorus scatterer. The arrow indicates the calculated position of the long wavelength Bragg cutoff. At some neutron inverse velocities two independent measurements of the direct and scattered neutron spectra were made.

with the literature values of the absorption cross section so that there are no absorbing impurities in our sample. Also, by using a thinner scatterer, we have shown that the apparent large absorption cross section for the *scattered* neutrons is not due to multiple scattering. Therefore, we are forced to assume that the decrease in $k$ with increasing neutron wavelength is mostly due to temperature scattering effects[14] and that, hence, Eq. (8) is not applicable to Fig. 7. Although we have not compared the shape of our curve with the rather complicated[14] and by no means certain[41] calculations on temperature scattering, we feel that we were justified in calculating the hardening factor for phosphorus by using the experimentally determined $k$ values (Fig. 7).

[37] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 105.

[38] G. Natta and L. Passerini, Nature **125**, 707 (1930).

[39] H. Pomerance, unpublished, quoted by K. Way *et al.*, *Nuclear Data* (Nat. Bur. Standards Circ. No. 499, 1950). See also F. C. W. Colmer and D. J. Little, Proc. Phys. Soc. (London) **A63**, 1175 (1950).

[40] M. Ross and J. S. Story, Progress Reports in Physics **12**, 291 (1949).

[41] J. M. Cassels and R. Latham, Phys. Rev. **74**, 103 (1948).