Scattering of Neutrons by Deuterons*

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Angular distributions and total cross sections for neutrons scattered by deuterons were measured at various neutron energies ranging from 220 kev to 3 Mev. A proportional counter filled with deuterium was irradiated with monoenergetic fast neutrons produced by bombarding thin lithium and tritium-filled zirconium targets with protons from the electrostatic generator. Angular distributions of the neutrons scattered by deuterons were determined by measuring the distribution in energy of the recoiling deuterons with a differential discriminator. Total neutron-deuteron cross sections were measured by comparing the neutron transmission of heavy water with ordinary water. Phase shifts determined from an analysis of the data were not in agreement with theoretical conclusions of Buckingham and Massey or of Verde.

I. INTRODUCTION

THE lack of any marked success in determining the properties of the nucleon-nucleon interaction in odd states, and hence the exchange character of nuclear forces, from nucleon-nucleon scattering experiments has led to an interest in the scattering of neutrons and protons by deuterons. Because of the large radius of the deuteron, relatively low energy neutrons and protons are strongly scattered in states of angular momentum greater than zero. Detailed calculations by Buckingham, Massey, and Hubbard[1,2] and by Verde[3] have shown that, in particular, the sign and magnitude of the P-wave phase shifts should be strongly affected by the exchange character of nuclear forces.

Although there have been many determinations of neutron-deuteron angular distributions[4–10] and total cross sections,[11–13] it has been difficult to reach any definite conclusions as to the role of exchange forces in the $n-d$ interaction. Since the theoretical calculations are based on nuclear force models which do not adequately explain nucleon-nucleon scattering, one should not expect phase shifts calculated in this way to be more than qualitatively reliable. The differential cross sections are a sensitive function of the combination of at least six phase shifts at energies at which the main experimental results exist; therefore it is difficult to learn much from comparisons of theoretical and experimental differential cross sections.

It would be preferable to compare calculated phase shifts with phase shifts determined from analysis of the experimental results. However, even disregarding experimental uncertainties, which are not small in these measurements, neutron-deuteron differential cross section measurements cannot determine a unique set of phase shifts unless restrictions are imposed on the phase shifts from other considerations than the data alone. Recent measurements[14,15] concerning the neutron-deuteron scattering lengths have made it possible to make reliable estimates of S-wave phase shifts up to neutron energies of a few Mev by using an effective range approximation.[16] It then appeared that angular distribution and total cross section measurements at low energies where D-waves would not be important, might determine P-wave phase shifts which could be compared with phase shifts calculated by using various exchange force prescriptions.

II. TOTAL CROSS SECTION MEASUREMENTS

Measurements of the difference between the total neutron-deuteron cross section and the neutron-proton cross section were made by comparing the transmissions for monoenergetic neutrons of brass cans filled with heavy water and similar cans filled with the same number of molecules per cm^2 of ordinary water. The heavy water, obtained from Stuart Oxygen Company, was stated to be 99.8 percent pure by the supplier; a measurement of the density confirmed this value within an error of one percent. Transmissions were determined in a manner similar to that previously reported.[17]

For measurements at neutron energies greater than 900 kev, monoenergetic neutrons were produced by bombarding thin tritium-filled zirconium targets with protons from the electrostatic generator. The target was found to be 25 kev thick for 3.5-Mev protons by measuring the experimental width of the 2.08-Mev neutron scattering resonance in carbon.[17] This level has

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1 R. Buckingham and H. Massey, Proc. Roy. Soc. (London) **A179**, 123 (1941).
2 Buckingham, Hubbard, and Massey, Proc. Roy. Soc. (London) **A211**, 183 (1952).
3 M. Verde, Helv. Phys. Acta **22**, 339 (1949).
4 J. H. Coon and H. H. Barschall, Phys. Rev. **70**, 592 (1946).
5 J. H. Darby and J. B. Swann, Australian J. Sci. Research **A1**, 18 (1948).
6 E. Wantuch, Phys. Rev. **84**, 169 (1951).
7 Hamouda, Halter, and Sherrer, Phys. Rev. **79**, 539 (1950).
8 I. Hamouda and G. Montmoulin, Phys. Rev. **83**, 1277 (1951).
9 J. H. Coon and R. F. Taschek, Phys. Rev. **76**, 710 (1949).
10 Griffith, Remley, and Kruger, Phys. Rev. **79**, 443 (1950).
11 Nuckolls, Bailey, Bennett, Bergstralh, Richards, and Williams, Phys. Rev. **70**, 805 (1946).
12 H. Aoki, Proc. Phys. Soc. Japan **21**, 232 (1939).
13 Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
14 D. G. Hurst and W. F. Alcock, Can. J. Research **29**, 36 (1951).
15 Wollan, Schull, and Koehler, Phys. Rev. **83**, 700 (1951).
16 H. A. Bethe, Phys. Rev. **76**, 38 (1949).
17 Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).

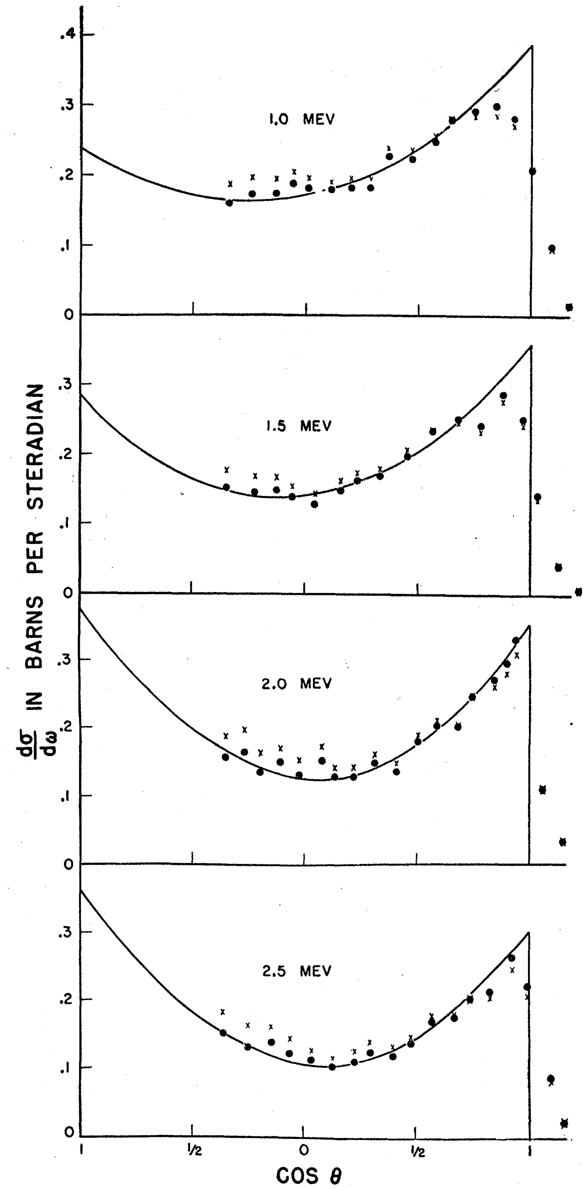

FIG. 1. Angular distributions in the center-of-mass system of neutrons scattered by deuterons at neutron bombardment energies of 1 Mev, 1.5 Mev, 2 Mev, and 2.5 Mev. The crosses represent the uncorrected data. The solid circles represent the data corrected for end effects and wall effects. The solid curve shows the distribution calculated from the phase shifts of Fig. 4.

been found to have a natural width of less than 10 kev. The neutrons were detected by a cylindrical pulse ionization chamber which had an active volume $\frac{15}{16}$ in. in diameter and 4 in. long. For detection of high energy neutrons the counter was filled with 43 atmospheres of purified hydrogen. A pulse-height discriminator eliminated pulses of less than one-half the incident neutron energy, in this way reducing the background, which is mainly caused by room-scattered neutrons, to less than one percent.

Below 900 kev it seemed advantageous to make use of the larger flux available from the Li(p, n) reaction. It was necessary to operate the counter at reduced pressures to improve the signal-to-noise ratio. Presumably the increased mobility of the electrons results in a larger voltage change during the time determined by the clipping time constant of the amplifier. The thickness of the target was found to be 25 kev by measuring the apparent width of the narrow 820-kev scattering resonance in beryllium.[17]

The cylindrical brass cans were constructed from 0.032 in. brass. Various lengths were used throughout the measurements in an effort to keep the transmission of the can containing ordinary water above 40 percent, thereby reducing uncertainties from multiple scattering into the detector. The scatterer was placed 7 in. from the source and 7 in. from the detector. With this geometry, the attenuation of the beam results from removal of all neutrons scattered through angles greater than 8° by the scatterer. Corrections, which considered the probable angular distribution of the scattered neutrons, were made for neutrons scattered into the counter.

The second column of Table I presents the measured cross section differences and their probable errors. Uncertainties in the inscattering corrections, the number of nuclei per cm^2, and the statistical standard deviation were considered in estimating the probable error. Column b shows the neutron-proton cross section calculated from the effective range theory[16] using as parameters[18,19] $A_s = -23.7\times10^{-13}$ cm, $A_t = 5.38\times10^{-13}$ cm, $\rho_t = 1.704\times10^{-13}$ cm, and $\rho_s = 2.5\times10^{-13}$ cm. Cross sections calculated from these parameters are in agreement with the results of measurements recently made in this laboratory.[20] Column c represents the neutron-deuteron cross section calculated from columns a and b. Probable errors can be considered to be about equal to those in column a.

The values are in agreement with early work of Aoki[12] and of the Minnesota group.[11]

III. ANGULAR DISTRIBUTIONS

Angular distributions of neutrons scattered by deuterons were determined using a method similar to that previously reported.[21] Monoenergetic neutrons were used to bombard deuterium in a proportional counter and the angular distribution of the scattered neutrons was determined by measuring the distribution in energy of the deuteron recoils. Barschall and Kanner[22] have pointed out that this distribution is proportional to the differential scattering cross section per unit solid angle as a function of $\cos\vartheta$, where ϑ is the angle of scattering in the center-of-mass system. The propor-

[18] Burgy, Ringo, and Hughes, Phys. Rev. **84**, 1160 (1951).
[19] E. E. Salpeter, Phys. Rev. **82**, 60 (1951).
[20] Fields, Becker, and Adair, Bull. Am. Phys. Soc. **27**, No. 5, 23 (1952).
[21] R. K. Adair, Phys. Rev. **86**, 155 (1952).
[22] H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).

tional counter was the same as used previously. Pulse-height distributions were measured with a single-channel differential discriminator. A channel width of $2\frac{1}{2}$ volts was used. The position of the bottom of the channel could be varied from 0 to 50 volts.

Measurements of the $n-d$ angular distributions at neutron energies of 1 Mev, 1.5 Mev, 2 Mev, and 2.5 Mev were made by irradiating the counter with fast neutrons from the $T(p, n)$ reaction. The tritium target was the same as used for the total cross section measurement. For these measurements the counter was filled with 20 cm of deuterium, and sufficient argon was added to reduce the recoil track length of deuterons scattered in the forward direction to about 9 mm. The total pressure, therefore, was varied with the neutron energy. A gas multiplication of about ten was obtained with about 3000 volts on the center wire and 800 volts between the wire and guard sleeve. A set of ten $B^{10}F_3$ filled proportional counters encased in paraffin was used to monitor the neutron flux. Measurements were made with the active volume of the counter in line with the proton beam and about 7 in. from the source. Backgrounds, determined by interposing a 10-in. cone of paraffin between the counter and the source, were found to be negligible. The crosses on Fig. 1 indicate the pulse-height distributions obtained in this way; the ordinate of each point is proportional to the number of counts in the channel per unit neutron flux, and the abscissa is proportional to the bias voltage measured to the center of the channel.

Slightly different procedures were used to obtain the angular distributions at energies of 220 kev, 500 kev, and 750 kev. Since the low energy group of neutrons from the $Li(p, n)$ reaction will not interfere with measurements at these energies, it seemed again advantageous to make use of the greater flux from this reaction. For measurements at 220 kev the chamber was filled with 78 cm of deuterium and operated at a gas multiplication of about 30. The crosses in Fig. 2 show the distributions obtained with the neutrons produced by bombarding a 25-kev thick lithium target with protons from the electrostatic generator.

TABLE I. Total neutron cross section of deuterium. Column *a* gives the experimental difference in the neutron-proton and neutron-deuteron cross section in barns for 9 values of neutron energy in Mev. Column *b* gives the $n-p$ cross section calculated from effective range theory. Column *c* is obtained by subtracting column *a* from column *b*.

E_n	*a*	*b*	*c*
0.262	5.25–0.11	8.47	3.22
0.593	2.62–0.10	5.60	2.98
0.872	1.67–0.08	4.57	2.90
1.178	1.18–0.10	3.89	2.71
1.505	0.82–0.09	3.41	2.59
1.772	0.49–0.05	3.11	2.62
2.185	0.34–0.04	2.76	2.42
2.598	0.21–0.04	2.49	2.28
2.962	0.19–0.03	2.30	2.11

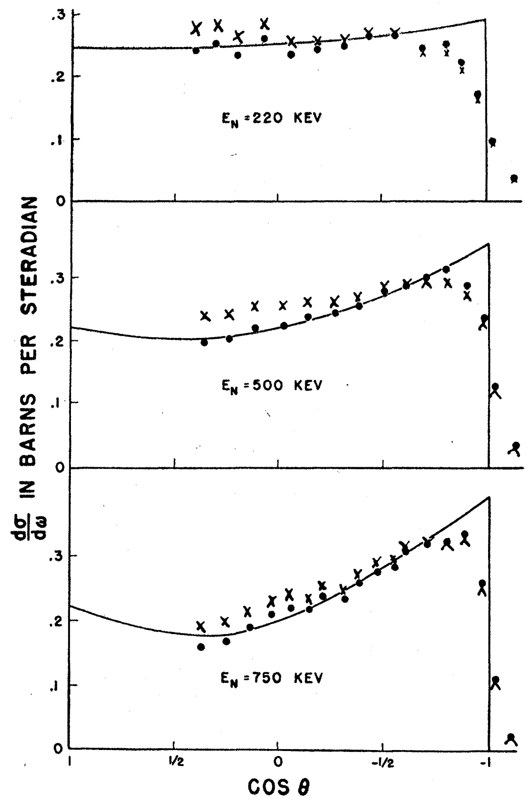

FIG. 2. Angular distributions in the center-of-mass system of neutrons scattered by deuterons at neutron bombardment energies of 220 kev, 500 kev, and 750 kev. The crosses represent the uncorrected data. The solid circles represent the data corrected for end effects and wall effects. The solid curve shows the distribution calculated from the phase shifts of Fig. 4.

Corrections must be made to pulse-height distributions before one can relate them to differential cross sections. In particular, allowance must be made for tracks which enter or leave the active volume expending only part of their energy in this volume. Recoils of each energy E are lost when deuterons of this energy strike the walls or leave the active volume of the counter by passing out of the end. Spurious pulses of energy E are produced when recoils of energy greater than E leave the active volume of the counter after losing only the fraction of this energy equal to E in the active volume. In computing corrections for these effects it was assumed, for simplicity, that the active volume ended sharply at planes normal to the center wire intercepting the ends of the guard sleeves. Corrections were then calculated numerically using deuteron range-energy curves. The uncertainty in the correction is estimated to be equal to about one-third of the correction and is of the same magnitude as the purely statistical errors.

The solid circles on Fig. 1 and Fig. 2 represent the corrected pulse-height distributions. Since the pulse-height distribution is proportional to the angular distribution, the circles also represent differential cross

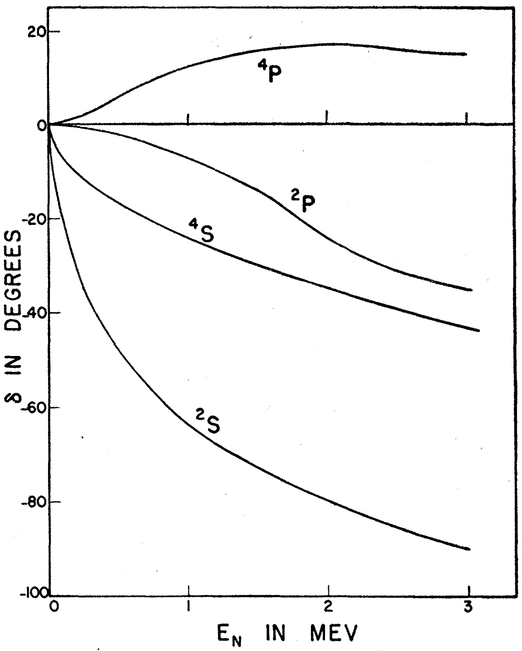

FIG. 3. Phase shifts for neutron-deuteron scattering.

sections. The ordinate is scaled so that a reasonable extension of the distribution to small angles results in a total cross section in agreement with the measured values. We estimate that the differential cross sections determined in this way are reliable to within about 15 percent, except at 180° where the poor resolution of the counter may give too low a value by a somewhat larger factor.

The results at 2.5 Mev are in excellent agreement with the measurements of Coon and Barschall.[4]

IV. INTERPRETATION

If we assume that the total spin of the system and its Z component are conserved, we can write the differential cross section for the scattering of neutrons by deuterons as

$$d\sigma/d\omega = k^{-2}\left[\tfrac{1}{3}\left|\textstyle\sum_l (2l+1)\,{}^2A_l P_l(\cos\vartheta)\right|^2 + \tfrac{2}{3}\left|\textstyle\sum_l (2l+1)\,{}^4A_l P_l(\cos\vartheta)\right|^2\right], \quad (1)$$

where $A_l = e^{i\delta_l}\sin\delta_l$ is the complex scattering amplitude for partial waves associated with orbital angular momentum l, the superscript on A represents the spin multiplicity, and δ is the scattering phase shift. At low energies we can assume that only S and P waves are scattered appreciably, and the cross section takes the form

$$d\sigma/d\omega = k^{-2}(A + B\cos\vartheta + C\cos^2\vartheta), \quad (2)$$

where

$$A = \tfrac{1}{3}\sin^2 {}^2\delta_0 + \tfrac{2}{3}\sin^2 {}^4\delta_0,$$

$$B = 2\sin^2\delta_0 \sin^2\delta_1 \cos({}^2\delta_0 - {}^2\delta_1) + 4\sin^4\delta_0 \sin^4\delta_1 \cos({}^4\delta_0 - {}^4\delta_1),$$

$$C = 3\sin^2 {}^2\delta_1 + 6\sin^2 {}^4\delta_1.$$

It is obviously not possible to extract the four phase shifts from the three parameters, A, B, and C, available from the experimental measurements.

It appears possible, however, to make a unique determination of the phase shifts by requiring them to behave in a physically plausible manner, and to be consistent with the zero energy scattering lengths. The antisymmetrization of the wave function required by the Pauli principle results in effective regions of repulsion in ${}^4S$, ${}^2P$, ${}^4D$ states, etc. These phase shifts might then be expected to be less positive than the ${}^2S$, ${}^4P$, ${}^2D$ phases. Since there exists a state of the doublet system bound by about 6 Mev, the ${}^2S$ radial wave function should have a node at about the triton radius. The ${}^2S$ phase shift should, therefore, lie in the second quadrant and the scattering length should be positive and of the same magnitude as the triton radius.

Two sets of scattering lengths are consistent with the low energy neutron-deuteron scattering data;[14,15] ${}^2a = 0.7\pm0.3\times10^{-13}$ cm, ${}^4a = 6.38\pm0.06\times10^{-13}$ cm, and ${}^2a = 8.26\pm0.12\times10^{-13}$ cm, ${}^4a = 2.6\pm0.2\times10^{-13}$ cm. Only the latter set is in agreement with the existence of a nearby bound state of the triton.

Gordon[23] has pointed out that if one accepts the charge symmetry of nuclear forces, the low energy proton-deuteron scattering measurements establish this choice of scattering lengths. Theoretical calculations by Troesch and Verde[24] are in good agreement with these values, though the results of Buckingham and Massey are less satisfactory in this respect.

It is possible to estimate the S-wave phase shifts by using the scattering lengths and the effective range approximation,[16] $k\cot\delta = -1/a + \frac{1}{2}\rho k^2$. The scattering lengths[14,15] used were ${}^2a = 8.3\times10^{-13}$ cm and ${}^4a = 2.7\times10^{-13}$ cm. The phases are not very sensitive to the range ρ, which was taken, rather arbitrarily, as 5×10^{-13} cm. Since scattering amplitudes are not affected by a shift of 180°, the ${}^2S$ phases are represented in the fourth quadrant for convenience.

An interesting characteristic of the scattering is the shift in the asymmetry of the angular distribution with energy. At low energies back scattering is predominant, while at higher energies there is some indication that most of the scattering is in the forward direction. Other workers[5,8–10] have shown that this trend continues to higher energies. Since the S-wave phase shifts are both negative, Eq. (2) shows that back scattering is the result of interference between the S waves and P waves which have a positive phase shift. Forward scattering must be due to the interference effects of S waves and P waves with a negative phase shift. The angular distribution at 1.5 Mev has a large P-wave contribution quadratic in $\cos\vartheta$, but is nearly symmetric about 90°. This can only occur if the asymmetric $S-P$ interference terms from doublet and quartet states are of opposite signs and cancel. This will occur if the ${}^2P$ and

[23] M. M. Gordon, Phys. Rev. **80**, 1111 (1950).
[24] A. Troesch and M. Verde, Helv. Phys. Acta **24**, 39 (1951).

^4P waves are of opposite sign. From our considerations regarding the effects of the exclusion principle, we see that the ^4P-wave phase shift must be positive and the ^2P-wave phase shift negative. At low energies the $^4P^4S$ interference term, resulting in back scatterings, is more important than the $^2P^2S$ term which gives rise to preferential scattering in the forward direction. At higher energies the $^2P^2S$ term is dominant. Figure 3 shows S- and P-wave phase shifts as a function of energy. They were adjusted by trial and error to best fit the data. The phase shifts were required to change smoothly with energy and to vary[25] as $E^{(2l+1)/2}$ at low energies. Above 750 kev, S-wave phases a little smaller than calculated by the effective range parameters best fit the data. The solid curves on Fig. 1 and Fig. 2 show differential cross sections calculated with these phase shifts. The solid curve on Fig. 4 shows the total cross section calculated from the phase shifts, while the points represent the experimental determinations.

At the higher energies the effects of D waves probably will not be negligible. These effects may be most evident in $P-D$ interference terms in $\cos^3\vartheta$. Since the neutron-deuteron angular distributions are particularly unreliable at 180° where the D-wave contributions might be large, any estimate of the D-wave phase shifts must be obtained from another source. Measurements[26] of the proton-deuteron differential scattering cross section are quite accurate. If nuclear forces are charge symmetric the proton-deuteron phase shifts should differ from the neutron-deuteron phase shifts only because of Coulomb forces. While it is not possible to calculate the effects of Coulomb forces without a detailed understanding of the interaction, it is probable that the proton-deuteron phase shifts will be somewhat smaller than the neutron-deuteron phase shifts at the same energy. The points on Fig. 5 show the experimental values for the proton-deuteron differential cross section at 2.53 Mev. The solid curve is calculated from phase shifts similar to but smaller than the neutron-deuteron phase shifts at 2.5 Mev. The phase shifts were adjusted to fit the experimental results at 125° and 55°, angles where the D wave vanishes. The dotted curve shows the differential cross section with the added contributions of a ^2D-wave phase shift of $+7°$ and a ^4D-wave phase shift of $+1°$. Cumulative effects of uncertainties in the approximations made are sufficiently great so that the values of the D-wave phase shifts are of only qualitative significance.

It can be shown that the measurements of Wantuch[6] at 4.5 Mev and 5.5 Mev are not in contradiction with an interpretation in terms of phase shifts resulting from an extrapolation of the phases in Fig. 3. Though this conclusion is in disagreement with the statement of Latter and Latter[27] that the S-wave phase shifts are "almost certainly positive," it is not in contradiction with the careful survey made by these authors of the possible combinations of phase shifts which could fit both the neutron-deuteron and proton-deuteron data. Slight adjustments of the phase shifts listed as $u=1$ $(1+-)$ in the notation of their article are consistent both with our low energy conclusions and the 5-Mev data.

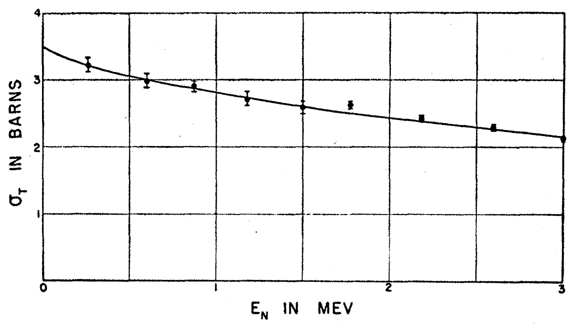

FIG. 4. The neutron-deuteron total cross section as a function of neutron bombarding energy. The points represent the experimental values while the solid curve represents values calculated from the phase shifts of Fig. 3.

It has been assumed in this discussion that the Z component of the total spin of the system is a good quantum number. In view of the strong spin orbit interactions observed in other neutron scattering experiments[21] and the importance of tensor forces in nuclear interactions, it would appear that the neglect of spin orbit coupling may not be realistic. Considering only S and P waves, the differential scattering cross section, with spin orbit coupling, takes the form

$$\begin{aligned}\frac{d\sigma}{d\omega}=\frac{1}{3k^2}\Bigg[&\left|{}^4A_0^{3/2}+\left(\frac{6}{5}{}^4A_1^{5/2}+\frac{9}{5}{}^4A_1^{3/2}\right)\cos\vartheta\right|^2\\&+\left|\frac{3\sqrt{3}}{5}{}^4A_1^{3/2}-\frac{3\sqrt{3}}{5}{}^4A_1^{5/2}\right|^2\sin^2\vartheta\\&+\left|{}^4A_0^{3/2}+\left(\frac{9}{5}{}^4A_1^{5/2}+\frac{1}{5}{}^4A_1^{3/2}+{}^4A_1^{1/2}\right)\cos\vartheta\right|^2\\&+\left|\frac{1}{2}{}^4A_1^{1/2}+\frac{2}{5}{}^4A_1^{3/2}-\frac{9}{10}{}^4A_1^{5/2}\right|^2\sin^2\vartheta\\&+\left|\frac{3\sqrt{3}}{10}{}^4A_1^{5/2}+\frac{\sqrt{3}}{5}{}^4A_1^{3/2}-\frac{\sqrt{3}}{2}{}^4A_1^{1/2}\right|^2\sin^2\vartheta\\&+\left|{}^2A_0^{1/2}+(2\,{}^2A_1^{3/2}+{}^2A_1^{1/2})\cos\vartheta\right|^2\\&+\left|{}^2A_1^{1/2}-{}^2A_1^{3/2}\right|^2\sin^2\vartheta\Bigg],\end{aligned}\quad(3)$$

where the added right-hand superscript on the scattering amplitudes represents the total angular momentum of the scattered wave. The general effect of spin orbit forces on the differential cross section is to add to the

[25] E. P. Wigner, Phys. Rev. **73**, 1002 (1948).
[26] Sherr, Blair, Kratz, Bailey, and Taschek, Phys. Rev. **72**, 662 (1947).
[27] A. L. Latter and R. Latter, Phys. Rev. **86**, 727 (1952).

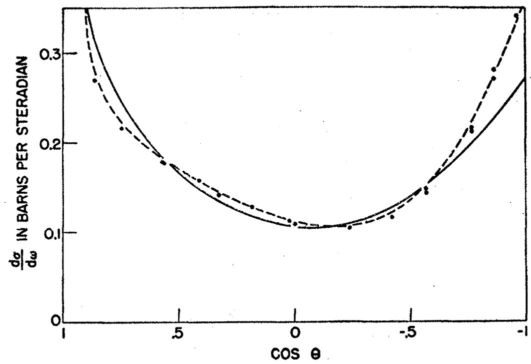

FIG. 5. Proton-deuteron angular distribution at 2.53 Mev. The points represent the experimental values of reference 26. The solid curve shows the angular distribution calculated using: $\delta(^4S)=-31°$, $\delta(^2S)=-80°$, $\delta(^2P)=-27°$, $\delta(^4P)=+15°$. The dotted curve shows the angular distribution calculated using the same S- and P-wave phases and $\delta(^4D)=+1°$ and $\delta(^2D)=+7°$.

isotropic part of the cross section and subtract from the terms which are quadratic in $\cos\vartheta$. The magnitudes of the terms in $\sin^2\vartheta$ of Eq. (3) are a measure of the kinematic importance of spin orbit forces. If the splitting, or angular difference, between the P waves associated with the same spin multiplicity but different total angular momentum be represented by Δ, the effect on the differential cross section will be of the order of $k^{-2}\sin^2\Delta$. This will be quite small compared to the isotropic term, unless the splitting Δ is of the same magnitude as the phase shifts of the P waves themselves. There is some evidence that the ^2P splittings are not large. Gamma-rays produced by the capture of protons by deuterons are emitted in a nearly pure $\sin^2\vartheta$ distribution.[28] and Wilkinson[29] has shown that they are almost completely polarized. This is explained as the result of an electric dipole transition from ^2P to ^2S state. In order that the angular distribution be nearly pure $\sin^2\vartheta$ it is necessary for $^2P^{\frac{3}{2}}$ and $^2P^{\frac{1}{2}}$ waves to be captured in the ratio of their statistical weights, an improbable occurrence if the two waves were refracted very differently.

It appears that little error is introduced in assuming the conservation of spin. Doublet-quartet transitions can only occur if the orbital angular momentum changes two units. Since only S and P waves are expected to be important at the energies under consideration in this experiment, it would seem justifiable to neglect the effects of such transitions. At higher energies $^4S \rightleftharpoons {}^2D$, and $^2S \rightleftharpoons {}^4D$ transitions may be important. Their effect on the angular distribution would be to increase the isotropic part of the cross section at the expense of the angular dependent part.

V. DISCUSSION

Qualitatively the neutron-deuteron angular distributions at 1.5 Mev and above are quite similar to the proton-deuteron angular distributions, and it appears from Fig. 5 that both sets of data can be fitted with similar phase shifts, a result which is in agreement with the equivalence of neutron-neutron and proton-proton forces.[30] Critchfield[31] has analyzed the proton-deuteron scattering using an auxiliary assumption, from the theoretical conclusions of Buckingham and Massey, that the ^2S and ^4S phases are equal. Though the validity of this assumption has since been shown to be dubious by the low energy neutron-deuteron scattering data, the P-wave phases extracted by Critchfield should not be strongly affected by this. Since these phase shifts are very similar to those derived here from the neutron-deuteron scattering data, the general conclusions of Critchfield are in agreement with this work.

A direct comparison of the phase shifts derived from these data with those calculated by Buckingham, Massey, and Hubbard[2] reveals rather considerable differences. As was evident from the scattering lengths, their S-wave phase shifts do not adequately represent the experimental data. The P-wave phase shifts should, in general, be less positive for exchange forces than for ordinary forces as the nucleon-nucleon potentials are repulsive in the antisymmetric space states which occur in P-wave interactions.

Both of the measured P-wave phases are more negative than theoretical values calculated for ordinary forces, and the ^2P-wave phase shift is much more negative than even the phase calculated for exchange forces. S-wave phase shifts derived by Troesch and Verde[24] are in good agreement with the phases in Fig. 3 for both ordinary and exchange forces. However, the P waves calculated by these authors at 2.5 Mev do not appear to adequately represent the data.

It was shown that the kinematic effects of spin orbit forces are not likely to change these conclusions appreciably. Of course, this does not exclude the importance of such forces on the dynamics of the interaction. Such forces may account for some of the discrepancy between the theoretical work which was calculated on the basis of central forces, and the conclusions from the experimental data.

[28] Fowler, Lauritsen, and Tollestrup, Phys. Rev. **76**, 1767 (1949).
[29] D. H. Wilkinson, Phil. Mag. **341**, 659 (1952).
[30] G. Breit, Phys. Rev. **80**, 1110 (1950).
[31] C. L. Critchfield, Phys. Rev. **73**, 1 (1948).