Polarization in Neutron-Proton Scattering at 23.1 MeV*

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A measurement of *n-p* polarization has been made at 23.1 MeV neutron energy of higher precision and of greater angular range than data previously available. The $T(d,n)He^4$ reaction was used as a source of monoenergetic, highly polarized neutrons, and a solenoid was used to precess the incident spin polarization for the asymmetry measurements. The values of polarization for laboratory scattering angles of 25, 35, 45, 55, 65 and 75 deg were measured to be $+0.0492\pm0.0140$, $+0.0529\pm0.0100$, $+0.0522\pm0.0071$, $+0.0310\pm0.0071$, $+0.0247\pm0.0090$, and -0.0036 ± 0.0090, respectively. The Basel sign convention is used. Comparison is made with several theoretical predictions and differences between theory and experiment are found to be small.

AT 23 MeV, *S*-wave scattering has been augmented by the growth of *P* waves, and neutron-proton polarization is a significant observable. While unusual behavior of the polarization is not to be expected, precise data will serve to verify and strengthen the theory. On the experimental side, knowledge that the $T(d,n)He^4$ reaction provides high neutron polarization[1] together with good neutron intensity has made neutron polarization measurements near 20 MeV feasible. Polarization data for *n-p* scattering at 16.4 and 23.7 MeV have recently been published by Benenson, Walter, and May.[2] The results reported here at 23.1 MeV represent a substantial improvement in precision and angular range over the previous data. A group at Harwell[3] have also reported *n-p* polarization measurements covering a range of energies from 90 to 22.5 MeV. At the lowest energy, these data suffered from large errors caused partly by low beam polarization. References to earlier work on *n-p* polarization may be found in recent survey articles,[4,5] and a recent bibliography.[6]

The experimental geometry is shown in Fig. 1. Neutrons of 23.1 ± 0.1 MeV energy were produced from the $T(d,n)He^4$ reaction at an angle of 30°(lab) by 7 MeV deuterons incident on a tritium target. Under these conditions the neutron polarization is approximately 0.59.[1] The tritium was contained in a gas cell 2 cm long at a pressure of 66 psi absolute. For reasons of convenience, the reaction plane was chosen to be the vertical plane. Neutrons emitted downward from the source impinged on a cylindrical polystyrene scintillator, labeled *S*1, placed at a distance $R_1=48$ in. from the source. Neutrons scattered from protons in *S*1, at an angle θ_2, were detected by another plastic scintillator, *S*2. The scintillator *S*1 is a cylinder 1 in. diam by 2 in. high, while *S*2 is 2 in. wide (in $\Delta\theta$), 4 in. high (in $\Delta\phi$), and 3 in. deep. The distance R_2 between the scintillators was varied with angle, the values being recorded in Table I. A spin precession solenoid[7] was interposed between the source and *S*1 to precess the neutron polarization $\pm90°$, parallel or antiparallel to the normal of the *n-p* scattering plane. A tapered brass collimator was inserted in the solenoid bore to minimize in-scattering from the solenoid, and to reduce the neutron flux at *S*2. The neutron flux monitor was a plastic scintillator counter placed on the solenoid axis at a distance of approximately 70 in. from the source.

Neutron-proton scattering events were detected as fast coincidences between the proton recoils in *S*1 and *S*2. A block diagram of the electronics is shown in Fig. 2. The fast coincidence circuit,[8] used with 6810 A type photomultipliers, provided time resolution of approximately 6 *ns* full width at half-maximum. Pulse height requirements were placed on the signals from *S*1 and *S*2 by means of a fast linear gate[9] circuit and following slow coincidence circuit. The gate pulse was approximately 100 *ns* long and was triggered by the fast coincidence output. The gating circuits prevented the high singles rates, ($\approx10^5$ pulses/sec in *S*1) from entering the slow amplifiers or the pulse height analyzer.

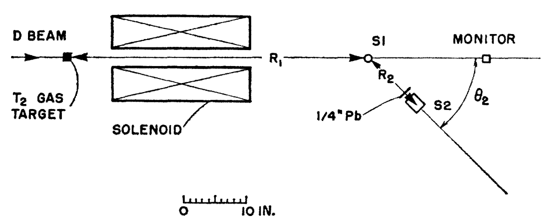

FIG. 1. The experimental geometry, as seen from the normal to the *n-p* scattering plane. *S*1 refers to the *n-p* scattering scintillator while *S*2 refers to the detector of the scattered neutron.

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[2] W. Benenson, R. L. Walter, and T. H. May, Phys. Rev. Letters **8**, 66 (1962).

[3] P. H. Bowen, G. C. Cox, G. B. Huxtable, A. Langsford, J. P. Scanlon, and J. J. Thresher, Phys. Rev. Letters **7**, 248 (1961).

[4] J. L. Gammel and R. M. Thaler, *Progress in Elementary Particle and Cosmic-Ray Physics*, (North-Holland Publishing Company, Amsterdam, 1960), Vol. 5, p. 99.

[5] M. H. MacGregor, M. J. Moravcsik, and H. P. Stapp, Ann. Rev. Nucl. Sci. **10**, 291 (1960).

[6] H. A. Stoddart and B. J. Wilson, Harwell Research Report, Atomic Energy Research Establishment BIB 135, 1961 (unpublished).

[7] Details will be found in a note to be submitted to the Rev. Sci. Instr.

[8] S. C. Baker, H. G. Jackson, and D. A. Mack, IRE Trans. Nucl. Sci. **NS-7**, 89 (1960).

[9] We are indebted to Professor Val Fitch for bringing this gate circuit to our attention. It is similar to that described by G. B. B. Chaplin and A. J. Cole, Nucl. Instr. Methods **7**, 45 (1960).

TABLE I. Measured values of neutron-proton polarization.

θ_2 (lab)	$\Delta\theta/2$	R_2 (in.)	e	Δe^a	$P_2{}^b$	ΔP_2
25°	2.4°	15	+0.0290	±0.0083	+0.0492	±0.0140
35°	3.6°	10	+0.0312	±0.0059	+0.0529	±0.0100
45°	3.6°	10	+0.0308	±0.0042	+0.0522	±0.0071
55°	3.6°	10	+0.0183	±0.0042	+0.0310	±0.0071
65°	3.6°	10	+0.0146	±0.0053	+0.0247	±0.0090
75°	5.2°	7	−0.0021	±0.0053	−0.0036	±0.0090

[a] The values of Δe are standard deviations.
[b] $P_2 = e/0.59$.

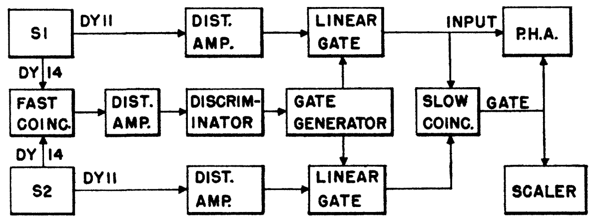

FIG. 2. Block diagram of the electronics.

Examples of pulse height distributions from $S1$ for three different angles are shown in Fig. 3. The distributions have been renormalized and plotted as functions of proton recoil energy with high bias points indicated by arrows and the low bias cut off by vertical lines. The corresponding distributions from $S2$ are not shown; their shape is reasonable, however. The accidental coincidence rate averaged less than 3% of the n-p coincidence rate except at 25° lab angle where it increased to 8%.

The measured asymmetry, e, is defined in terms of the counting rates as, $e=[I(+)-I(-)]/[I(+)+I(-)]$. In this equation, $I(+)$ and $I(-)$ represent net coincidence counting rates relative to the flux monitor, for the incident spin polarization vector precessed to be parallel or antiparallel, respectively, to $\mathbf{n}$, the normal to the scattering plane. The vector $\mathbf{n}$ is parallel to $\mathbf{k}_{\text{inc}}\times\mathbf{k}_{\text{final}}$; this definition corresponds to the Basel convention.[10] The sign of e, based on the calculation of the direction of neutron precession in the axial magnetic field, is consistent with the measured asymmetry in $n-He^4$ scattering done with the same experimental configuration. Let P_1 be the beam polarization, and P_2 the polarization in n-p scattering, then $e=P_1P_2$.

The results of this experiment are given in Table I. An estimate of the angular spread and the values of R_2 are entered for the sake of completeness. The angular spread, $\Delta\theta/2$, represents a standard deviation in the laboratory angle θ_2, and was calculated by mean square average of the geometrical widths of $S1$ and $S2$. The polarization results have not been corrected for angular resolution effects, since an estimate of the corrections involved showed that they were much smaller than the uncertainties in the data. The standard deviations listed for e are purely statistical at angles of 45° and greater; the errors at 25° and 35° have been increased by 10% over the statistical values as discussed below. At each angle at least 10 runs were made; the external errors so obtained agreed with the internal (statistical) errors. The values of P_2 listed in Table I were obtained by assuming $P_1=+0.59$.[1] The error in P_2 is based on the relative error in e, containing no contribution from the uncertainty in P_1. The uncertainty in P_1 arises from a continuing lack of knowledge of the n-He^4 analyzing power at 23 MeV.[1,11] We doubt, however, that this value for P_1 can deviate by more than ±0.1 from the true value. In support of this statement, we compared P_1 with the proton polarization in the charge symmetric reaction $He^3(d,p)He^4$, measured by Brown and Haeberli.[12] In their experiment, carbon was used as the analyzer. Interpolating their 30° lab data to the same deuteron energy (7 MeV), we obtained a proton polarization of +0.60±0.03. This value must be considered fortuitously close to the value of +0.59 we use for neutron polarization, especially since no account has been taken of the fact that the Q value of the $He^3(d,p)$ reaction is slightly greater than that of the $T(d,n)$ reaction.

We have used the solenoid to eliminate certain types of geometrical errors in the asymmetry. In so doing we acquire the possibility of errors arising from photomultiplier gain changes in the stray magnetic field of the solenoid. It is specially serious where we are trying to measure asymmetries to ±0.005. Magnetic field effects were reduced to practically zero by enclosing the solenoid in a box of 1-in.-thick steel,[7] and burying the photomultipliers in multiple shields of *mu* metal and steel. During the course of the experiment the magnetic asymmetry was measured in $S1$, $S2$ and the monitor counter using a Co^{60} gamma ray source; the effect was found to be consistent with zero to ±0.001. In an earlier preliminary experiment, of comparable statistical weight, we measured asymmetries in n-p scattering on the "left" and "right" sides of the deuteron beam. The expected reversal of sign of e occurred with no change in magnitude, which meant that no other gross source of instrumental asymmetry was present.

During the course of the experiment, several runs

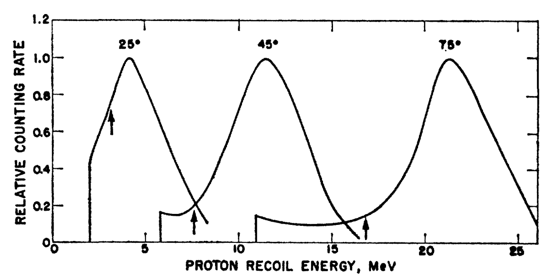

FIG. 3. Typical pulse height distributions of the recoil protons in $S1$ taken in coincidence with $S2$. The spectra taken under the low bias conditions are illustrated. The high bias conditions are indicated by the arrows.

[10] Helv. Phys. Acta, Suppl. VI, 436 (1961).
[11] S. M. Austin, H. H. Barschall, and R. E. Shamu, Phys. Rev. **126**, 1532 (1962).
[12] R. I. Brown and W. Haeberli, Phys. Rev. (to be published); R. I. Brown, thesis, University of Wisconsin, 1961 (unpublished).

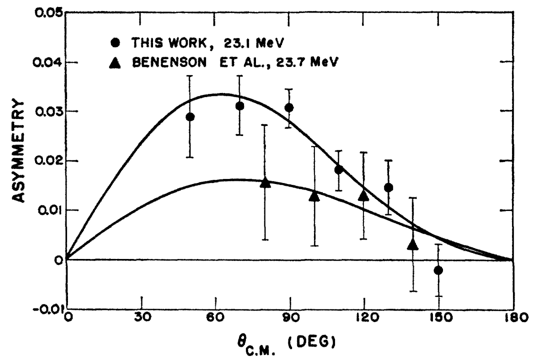

FIG. 4. Comparison between the measured asymmetries and those measured by Benenson *et al.* The solid lines through the data represent least squares fits to each set of data, using the form $e \propto \sin\theta(a+b\cos\theta)$.

were made with a 2-in.-diam scintillator substituted for $S1$ to check for possible influence of sample size on asymmetry; one thinks of multiple scattering in this connection. It was found that the asymmetries measured with the 2-in.-diam $S1$ were somewhat smaller on the average than those measured with the 1-in.-diam $S1$. The comparison is summarized as follows: define a ratio given by $e(\theta, 1\text{ in.})/e(\theta, 2\text{ in.})$. At the angles $\theta_2(\text{lab})=35$, 45, 55, and 65 deg, the ratio was found to be 1.36 ± 0.38, 1.43 ± 0.28, 0.86 ± 0.26, and 4.6 ± 7.5, respectively. Although the deviation from unity is not very significant, the ratio is greater than unity by a standard deviation at the first two angles. If multiple scattering effects are present in the 2-in.-diam $S1$, we expect that they should be greatly reduced by using the 1-in.-diam scintillator. In spite of the reduced counting rate, the data entered in Table I were all taken with the smaller size $S1$.

Other sources of systematic error must be examined. For example, the reaction $C^{12}(n,n'\gamma)$ occurs in $S1$ and under favorable conditions the 4.43 MeV gamma ray may be detected in $S1$ in coincidence with the inelastically scattered neutron in $S2$. The angle 25° is favorable for this background, since neither pulse height nor timing discriminates against it. An estimate of the effect was made using $C^{12}(n,n'\gamma)$ cross sections[13] at 14 MeV, and estimating the detection efficiency of the gamma ray in polystyrene from Compton scattering. Let f be the fraction of $(n,n'\gamma)$ coincidences compared to n-p events, let e_m be the measured asymmetry, let e be the true n-p asymmetry, and let e' be the asymmetry in the $(n,n'\gamma)$ reaction. Then we have $e_m=(e+fe')/(1+f)$ and, if f is small, $e_m\approx e+fe'$. The value of f is estimated to be 0.027, 0.021, 0.012, 0.004, 0, 0, at angles θ_2 ranging from 25° through 75°, respectively; this includes the effect of time discrimination at the larger angles. The value of e' is entirely unknown. If e' were equal to 0.2, the correction term fe' at 25° would be 0.0054, and smaller at other angles. Correction terms of this size are less than our error at 25°. In any case we do not make any correction to the data or any increase in the quoted errors, but we call attention to this potential correction.

Another possible source of coincidence background is the 13.37 MeV beta decay of B^{12} which is generated in the $C^{12}(n,p)B^{12}$ reaction[14] above 13.6 MeV neutron energy. These beta particles are prevented from entering $S2$ from $S1$ by 0.25 in. of lead interposed between the two counters, and therefore, they do not affect our results. At large angles, time delay and bias in $S1$ also discriminate against them. It is important to recognize this source of background, even though the total cross section for the reaction is relatively small, since the betas are detected with almost unit efficiency in $S1$ and $S2$. We have also considered contamination by the reaction[15] $C^{12}(n,n'3\alpha)$. Owing to their low light output in orgainic scintillators, the alpha pulses in $S1$ are lower than the bias except at laboratory angles of 25 and 35 deg. The fraction of neutrons reaching $S2$ suffer a further time discrimination. A rough calculation for 25° indicates that the contamination from this source is less than one percent; therefore, the $C^{12}(n,n'3\alpha)$ background is negligible. Likewise, the $C^{12}(n,2n)C^{11}$ reaction is of negligible importance because of its high threshold energy of 20.3 MeV.

In Fig. 3 the gated pulse height distributions for $S1$ are shown, the arrows indicating a "high" bias level under which the results of Table I were obtained. We have also measured the asymmetries utilizing the full

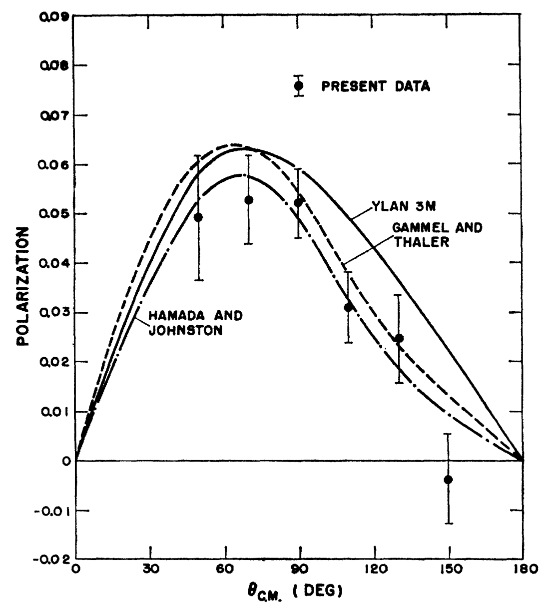

FIG. 5. Comparison between the measured polarization and several theoretical predictions. The dot-dashed curve is the prediction of Hamada and Johnston, the dashed curve is a prediction of Gammel and Thaler, and the solid curve is the prediction of YLAN3M.

[13] J. D. Anderson, C. C. Gardner, J. W. McClure, M. P. Nakada, and C. Wong, Phys. Rev. **111**, 572 (1958).

[14] W. E. Kregger and B. D. Kern, Phys. Rev. **113**, 890 (1959).

[15] G. M. Frye, Jr., L. Rosen, and L. Stewart, Phys. Rev. **99**, 1375 (1955).

TABLE II. Fit of the data of Table I to $I(\theta)P(\theta)=\sin\theta(a+b\cos\theta)$.

Fit[a]	a	Δa[b]	b	Δb[b]	$\langle\Delta a\Delta b\rangle_{av}$[b]
1	+0.0475	±0.0043	+0.0378	±0.0108	$+0.33\times10^{-4}$
2	+0.0464	±0.0043	+0.0367	±0.0108	$+0.33\times10^{-4}$

[a] For fit 1, $I(\theta)=1$; for fit 2, $I(\theta)=0.9665\ (1-0.008\cos\theta+0.104\cos^2\theta)$.
[b] Least square errors as defined in Eq. (30), J. Orear, University of California Radiation Laboratory Report UCRL-8417, 1958 (unpublished).

distributions shown in Fig. 3, which are called the "low" bias conditions. The ratio (e-high bias)/(e-low bias) was measured to be 1.10, 1.05, 1.01, 1.03, 1.00, and 1.10 at angles 25° through 75°, respectively. These numbers and the "tail" of the pulse height distributions indicate the possibility of a small, unknown source of background at small angles. On this account the errors in e at 25° and 35° were increased by 10% over their statistical values.

In Fig. 4 we compare our asymmetry results as a function of c.m. angle with the corresponding results of Benenson, Walter, and May.[2] Comparison of the polarizations directly involves the question of the best value of beam polarization; they used 0.46 at $E_N=23.7$ MeV, and we use 0.59 at $E_N=23.1$ MeV. Since they did not tabulate the equivalent asymmetry, we calculate it from $e=0.46P_2$, scaling the errors down accordingly. The curves shown in Fig. 4 represent a least squares fit to each set of data of the form $e\propto\sin\theta(a+b\cos\theta)$, where θ is the c.m. angle. Their two smallest angle data points are appreciably lower than the curve through our data.

The polarization data given in Table I have been fitted by the method of least squares to the theoretically expected form.[16] For S and P waves only, the predicted shape is $I(\theta)P(\theta)=\sin\theta(a+b\cos\theta)$, where θ is the c.m. angle and $I(\theta)$ is the unpolarized differential cross section. We have fitted our data in two ways: (1) assuming $I(\theta)$ is isotropic, and (2) using the recent experimental results of Flynn and Bendt[17] for $I(\theta)$ at 22.5 MeV. In the first case we simply set $I(\theta)=1$. In the second case, we take $I(\theta)=(A_0+A_1\cos\theta+A_2\cos^2\theta)/(A_0+A_2/3)$, where $A_1/A_0=-0.008$ and $A_2/A_0=+0.104$ as determined by fitting the data of Flynn and Bendt.[17] The results are shown in Table II. Clearly, the errors in a and b are much larger than the change due to the different assumptions of the shape of $I(\theta)$. The coefficients a and b form two equations of restraint on the triplet phase shifts at this energy. Phillips[18] has discussed the usefulness of the equation involving $P(90°)$ in restricting the triplet P phase shifts sets obtained by MacGregor[19] for proton-proton scattering at 20 MeV, assuming charge independence. The present data make the restrictions more severe.

In Fig. 5, a graphical comparison of our data and certain theoretical predictions is made. For complete references to theoretical work on the nucleon-nucleon system, the reader is referred to recent survey articles.[4,5,20,21] The solid curve labeled YLAN3M is a calculation[22] of polarization at 24 MeV based on results of an energy dependent phase shift analysis of the n-p system by Hull, Lassila, Ruppel, McDonald, and Breit.[23] These authors have discussed[22] the significance of low energy n-p polarization measurements relevant to the data of Benenson *et al.*[2] On the basis of the lower experimental values available at that time, Hull *et al.*[22] obtained a revised fit, YLAN3M′, which gave polarization values multiplied by a factor of 0.6. Figure 5 indicates that it is more the shape, rather than the over-all magnitude that should be modified, YLAN3M being rather too high at back angles as compared to the angles of peak polarization.

The dot-dashed curve in Fig. 5 has been calculated from phase shifts derived from a new potential-model representation of nucleon-nucleon scattering by Hamada and Johnston.[24] Their prediction provides an excellent fit to the data (it is as good as the empirical least squares fit, No. 1 of Table II). They used central, tensor, spin-orbit and quadratic spin-orbit terms in the potential, together with a fixed cut-off radius. The dashed curve was calculated from the potential models of Gammel and Thaler.[25] The triplet-even n-p phase shifts were obtained from an arbitrary choice of potential No. 4100 listed in reference 4. This potential has a cut-off radius of 0.4 F, a central well depth equal to the tensor depth, and no spin-orbit interaction. The singlet-odd parameters derive from a potential similar to that given by Gammel, Christian and Thaler,[26] while the singlet-even and triplet-odd phase shifts were obtained from the Gammel-Thaler[27] proton-proton potential. This fit is qualitatively similar to that of Hamada and Johnston,[24] but about 15% higher on the average.

Note added in proof. Professor G. Breit has supplied us with a graph of the polarization predicted by the Yale Potential at 23.1 MeV. [K. E. Lassila, M. H. Hull, H. M. Ruppel, F. A. McDonald, and G. Breit, Phys. Rev. **126**, 881 (1962).] This prediction very nearly matches that of Hamada and Johnston as shown in Fig. 5.

We wish to thank Dr. John Gammel and Dr. Michael Moravcsik for stimulating discussions on the subject of neutron-proton scattering.

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