Depolarization and Time Reversal in p-p Scattering at 142 Mev*

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The depolarization in proton-proton scattering at 142 Mev was measured at angles from 6° to 40° in the laboratory system.

The measurements were made by scattering a 67% polarized proton beam first off a liquid hydrogen target, then off a carbon (or lithium) analyzer. The scattered protons were detected by plastic scintillation counters, and the asymmetries from the last scattering were measured at each hydrogen scattering angle. The angular dependence of depolarization determined in this work was similar to that measured at 315 Mev by other workers. The data disagree with other measurements at 143 Mev.

By measuring on both sides of the beam, the polarization in scattering is determined and compared with asymmetry in scattering from a polarized beam. Their equality confirms time reversal invariance in the proton-proton interaction.

INTRODUCTION

THE discovery of the polarization effect associated with the nucleonic spins[1] greatly increased the number of observable quantities in the nucleon-nucleon interaction. The measurements of these observable quantities make it possible to determine the necessary parameters used to describe the nucleon-nucleon interaction in terms of phase shifts of the partial waves that enter into the interaction. The definitive data of Chamberlain *et al.*[2,3] and the associated phase-shift analysis by Stapp *et al.*[4] demonstrated the usefulness of this method.

In the absence of a complete set of experimental data for the nucleon-nucleon interaction at many energies, many workers, including Gammel and Thaler,[5] and Signell and Marshak,[6] have made calculations utilizing the available measurements to predict the nucleon-nucleon interaction at different energies. The Gammel-Thaler potential gives a good fit to available two-nucleon data up to 315 Mev. The Signell-Marshak potential gives a good fit to experimental data up to 150 Mev, but the fit becomes worse at 315 Mev. To determine the behavior of the phase shifts as functions of the energy of interaction, it is necessary to make measurements at many energies. For precisely this reason the proton-proton scattering program was initiated at the Harvard synchrocyclotron.

The first part of the Harvard proton-proton scattering program was the measurement by Palmieri *et al.*[7] of the differential cross section and polarization at various energies from 147 Mev down to 46 Mev. The present work concerns the measurement of the depolarization (hereinafter referred to as D) at 142 Mev at laboratory angles between 6° and 40°. A sequel to this work is the measurement of D at 98 Mev described in a companion paper.[8]

In this work, a polarized proton beam is directed onto a hydrogen target, and the polarization of the scattered beam is measured. The spin of the scattered proton is given by

$$\langle\boldsymbol{\sigma}\rangle_f=\frac{1}{1+P_1P_2\cos\phi_2}\{[P_2'+D\langle\boldsymbol{\sigma}\rangle_i\cdot\mathbf{n}_2]\mathbf{n}_2+[A\langle\boldsymbol{\sigma}\rangle_i\cdot\mathbf{K}_2+R\langle\boldsymbol{\sigma}\rangle_i\cdot(\mathbf{n}_2\times\mathbf{K}_2)]\mathbf{S}_2+[A'\langle\boldsymbol{\sigma}\rangle_i\cdot\mathbf{K}_2+R'\langle\boldsymbol{\sigma}\rangle_i\cdot(\mathbf{n}_2\times\mathbf{K}_2)]\mathbf{K}_2'\}. \quad (1)$$

Our notation differs from that of Wolfenstein[9] in that we distinguish P_2, the asymmetry produced at the hydrogen scattering by a completely polarized beam, from P_2', the polarization produced at the hydrogen scattering by an unpolarized beam. If the p-p interaction is invariant under time reversal, then $P_2=P_2'$.

When the plane of the polarizing scattering $\mathbf{n}_1$ and the plane of the hydrogen scattering $\mathbf{n}_2$ are coplanar,

$$\mathbf{n}_1\cdot\mathbf{n}_2=\cos\phi_2=\pm1, \quad (2)$$

$$\langle\boldsymbol{\sigma}\rangle_i\cdot\mathbf{n}_2=\pm P_1, \quad (3)$$

and

$$\langle\boldsymbol{\sigma}\rangle_f\cdot\mathbf{n}_1=(DP_1\pm P_2')/(1\pm P_1P_2). \quad (4)$$

General Description of the Experiment

A schematic diagram of the scattering arrangement in the measurement of D is given in Fig. 1. The com-

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[1] C. L. Oxley, W. F. Cartwright, J. Rouvina, E. Baskir, D. Klein, J. Ring and W. Skillman, Phys. Rev. **91**, 419 (1954); C. L. Oxley, W. F. Cartwright, and J. Rouvina, Phys. Rev. **93**, 806 (1954).

[2] O. Chamberlain, E. Segrè, R. D. Tripp, C. Wiegand, and T. Ypsilantis, Phys. Rev. **105**, 288 (1957).

[3] James E. Simmons, Phys. Rev. **104**, 416 (1956).

[4] H. P. Stapp, T. J. Ypsilantis, and N. Metropolis, Phys. Rev. **105**, 302 (1957).

[5] J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 291 (1957).

[6] P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958).

[7] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and Richard Wilson, Ann. Phys. **5**, 229 (1958).

[8] E. H. Thorndike and T. R. Ophel, following paper [Phys. Rev. **119**, 362 (1960)].

[9] L. Wolfenstein, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1956), Vol. 6, p. 43.

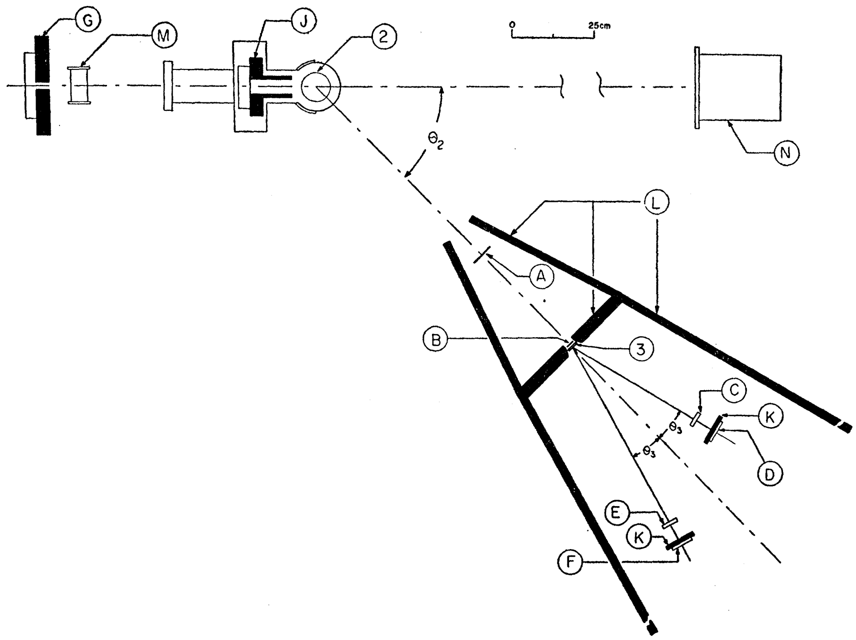

FIG. 1. Schematic diagram of the experimental arrangement for large angles ($\theta_2=20°$ to $40°$), showing: (2) hydrogen target, (3) analyzing scatterer, (A-F) scintillation counters, (G) main slits, (J) anti-scattering slits, (K) copper absorbers, (L) iron shielding, (M) ion chamber, and (N) Faraday cup.

ponents of this figure are referred to in the text by either numbers or letters in parentheses. The 146-Mev polarized proton beam[10] of the Harvard synchrocyclotron [polarized by a (first) internal scattering], was defined by slits (G) 1 in. wide by 3 in. high, and struck a target of liquid hydrogen (2), contained in a 4-in. diameter by $5\frac{1}{2}$-in. high cylindrical vessel made of 0.002-in. beryllium copper. Particles (doubly) scattered through an angle θ_2 in the horizontal plane, defined by counter B and the intersection of the beam with the hydrogen target, then struck the analyzing scatterer (3). Particles (triply) scattered through an angle θ_3 in the horizontal plane were detected by the counter telescopes CD or EF, placed on opposite sides of the twice scattered beam. Copper absorbers, placed in these telescopes enable one to reduce the number of inelastically scattered protons from the third scatterer that are accepted. The angle θ_3 of these counter telescopes could be reversed in sign. We denote the two senses as S and N, for scattering in the same or opposite sense, respectively, as the first scattering, occurring within the cyclotron, which gives the incident beam its polarization. Let $I(\theta_{2K},\theta_{3M})$ be the corrected rate of fourfold coincidences ($ABCD$ or $ABEF$) for scattering through angles θ_2 in the Kth sense and then through θ_3 in the Mth sense, where K, M are either S or N. Then we define

$$e_{3n}(\theta_{2K})=\frac{I(\theta_{2K},\theta_{3S})-I(\theta_{2K},\theta_{3N})}{I(\theta_{2K},\theta_{3S})+I(\theta_{2K},\theta_{3N})}. \quad (5)$$

If P_3 is the analyzing power of the third scattering, then

$$e_{3n}=P_3\mathbf{n}_1\cdot\langle\boldsymbol{\sigma}\rangle_f, \quad (6)$$

and hence

$$D(\theta_2)=[e_{3n}(\theta_{2S})(1+P_1P_2)+e_{3n}(\theta_{2N})(1-P_1P_2)]/2P_1P_3, \quad (7)$$

and

$$P_2'(\theta_2)=[e_{3n}(\theta_{2S})(1+P_1P_2)-e_{3n}(\theta_{2N})(1-P_1P_2)]/2P_3. \quad (8)$$

In the course of doing a triple scattering experiment, one also does a conventional double scattering experiment. If we define

$$I(\theta_{2K})=I(\theta_{2K},\theta_{3S})+I(\theta_{2K},\theta_{3N}), \quad (9)$$

and

$$e_2=[I(\theta_{2S})-I(\theta_{2N})]/[I(\theta_{2S})+I(\theta_{2N})], \quad (10)$$

then

$$e_2=P_1P_2. \quad (11)$$

The beam was monitored by an ionization chamber (M) placed before the hydrogen target, and a Faraday cup (L) placed after the hydrogen target.

Pulses from all six counters were fed to modified Garwin-type coincidence circuits[11] with resolving times of 30 nanosec and dead times of 150 nanosec.

ALIGNMENT

This experiment determines the asymmetry of the third scattering. It is therefore important to obtain the average direction of the twice scattered beam as a zero for the measurement of the third scattering angle θ_3. The profile of the twice scattered beam was determined by sweeping the counter telescopes C, D and E, F

[10] G. Calame, P. F. Cooper, Jr., S. Engelsberg, G. L. Gerstein, A. M. Koehler, A. Kuckes, J. W. Meadows, K. Strauch, and R. Wilson, Nuclear Instr. 1, 169 (1956).

[11] R. L. Garwin, Rev. Sci. Instr. 24, 618 (1953).

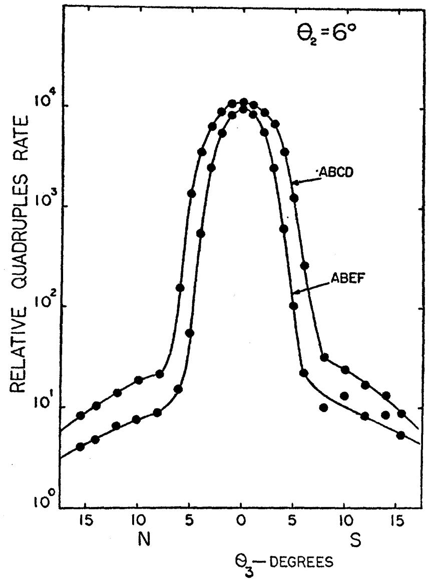

FIG. 2. Profiles of the twice-scattered beam, used to find the zero of the third scattering angle θ_3.

through the beam in turn. This was the procedure adopted by Chamberlain *et al.*[2]

Figure 2 shows a pair of such alignment profiles taken at the angle $\theta_2=6°$. It is seen that, as expected, the profile is symmetrical. On most occasions, therefore, only three points on the profile were measured, two on one side of the twice scattered beam and one on the other side. From these points the position of $\theta_3=0$ could be deduced to an accuracy of 0.025°. The counters were not again moved if the alignment was within 0.05°. The alignment was measured twice at each angle, once before the data collecting run and once afterwards. The average of the residual misalignments was used to correct the data. Thus the final data have a statistical error for a 0.025° misalignment which has been folded with the other errors.

An alternative procedure for alignment has also been used. The polarized beam was located by an x-ray film; the hydrogen target was located centrally on the midpoint of the beam and the pivot of the scattering table located immediately below the center of the target. The counters were accurately located on the arm. For a precision of 0.02° in θ_3, an accuracy of 0.01 inch is necessary in all the adjustments. This precision must be maintained in the presence of small movements of the beam, of motions of the liquid hydrogen target due to filling and of buckling of the scattering table while changing angles. The procedure is indirect and cannot be checked. Therefore, although no major discrepancy has appeared in the course of this work, the first method of alignment is preferred. Taylor[12] utilized only the second method of alignment and it is possible that this led to his different results.

The alignment for the zero of the scattering angle θ_2 was much less important. It was performed by sweeping counter B through the beam.

BACKGROUNDS

One type of background contribution came from the scattering of protons of the polarized proton beam by the antiscattering slits, the hydrogen can, the Mylar window, and the air in the proton path. By the proper choice of target construction and shielding, this contribution of background was restricted to be 3% of the hydrogen scattering at θ_2 greater than or equal to 20° in the laboratory (hereinafter, all angles referred to in this work are laboratory angles unless specified otherwise), increasing to 15% and 25% at θ_2 equal to 10° and 6°, respectively. This background contribution was measured and the data corrected. The background scattered protons were of lower energy during a data run than during a background run, because of the slowing down in the liquid hydrogen. Extra absorbers were placed in the telescope between counters C and D (also E and F) to compensate. There was, however, still a small correction because the cross sections and polarizations for the 2nd and 3rd scatterings are a function of energy.[13,14] This correction was made only at 6° and 10° where the background was appreciable.

Random coincidences in the $ABCD$ and $ABEF$ coincidence were also a source of background. They were determined by delaying pulses from the appropriate counters by 90 nanoseconds. This was exactly twice the period of the cyclotron fine structure and well outside the resolving time of the circuit. The random coincidence rate was calculated from the delayed coincidence rate by a knowledge of the true double and triple coincidence rates. The random counts between a genuine AB double coincidence and a genuine CD or EF double coincidence were found to be most serious, and varied from 1 to 3% of the total counting rate. They were nearly symmetrical so that systematic errors in their determination were not important. Random coincidences between a genuine BCD or BEF coincidence and counter A, or a genuine ABC or ABE coincidence and counter D or F were less than 0.1% and were neglected.

A third type of background contribution came from the scattering of the twice scattered proton beam by counter B and by air in the vicinity of the third scatterer. Since these background producing materials served in effect as additional third scatterers and since the product of polarizing power and analyzing power P_1P_3 was empirically determined, this particular background contribution had no effect on the measurement of D. e_{3n} was experimentally checked at $\theta_2=20°$

[12] A. E. Taylor and B. Wood, *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Feretti (CERN, Geneva, 1958), p. 56; A. E. Taylor (private communication).

[13] J. M. Dickson and D. C. Salter, Nuovo cimento **6**, 235 (1957).

[14] R. Alphonce, A. Johansson, and G. Tibell, Nuclear Phys. **4**, 672 (1957).

TABLE I. The experimental dimensions of the Harvard and Harwell D-apparatus.

Experimental component	Harvard apparatus	Harwell apparatus
Polarized proton beam	1 in. wide $\times 3$ in high at the defining slits. $67\pm 2\%$ polarization 146 ± 2 Mev	1 cm wide $\times 3$ cm high at the defining slits. 47% polarization 149 ± 1.5 Mev
Hydrogen target	4-in. diameter $\times 5\frac{1}{2}$ in. high, (0.7 g/cm² or 8 Mev thick) made of 2-mil beryllium copper. The polarized proton beam illuminated a $1\frac{1}{4}$ in. wide $\times 4$ in. high portion of this target.	15-cm diameter (6 in) 1.05 g/cm² or 12 Mev thick, made also of beryllium copper, no details available.
Counter A	2 in. wide $\times 6$ in. high $\times \frac{3}{32}$ in. thick located 31 in. from the center of the hydrogen target.	No equivalent of this counter in the Harwell apparatus.
Counter B	1 in. wide $\times 5$ in. high $\times \frac{3}{32}$ in. thick located 46 in. from the center of the hydrogen target.	2 cm wide $\times 3$ cm high $\times 1$ mm thick located 40 cm from the center of the hydrogen target.
Third scatterer	$1\frac{1}{2}$ in. wide $\times 6$ in. high, located within $\frac{1}{2}$ in. of Counter B. Thickness of 1 g/cm² for θ_2 of 35° and 40°; $1\frac{1}{2}$ g/cm² for θ_2 of 20°, 25°, and 30°; and 2 g/cm² for θ_2 of 6°, 10°, and 15°.	Information unknown.
Counter C	2 in. wide $\times 6$ in. high $\times \frac{3}{8}$ in. thick, located 18 in. from the center of the third scatterer.	3 cm wide $\times 4$ cm high $\times 1$ mm thick located 40 cm from the center of the third scatterer.
Counter D	3 in. wide $\times 8$ in. high $\times \frac{3}{8}$ in. thick, located 21 in. from the center of the third scatterer.	Information unknown.
Counter E	Same size as Counter C, located 27 in. from the center of the third scatterer.	No equivalent.
Counter F	Same size as counter D, located 30 in. from the center of the third scatterer.	No equivalent.

and 35°, by showing that the asymmetries were unaltered, when the third scatterer was removed.[15]

SPURIOUS ASYMMETRIES

There were several possible sources of spurious asymmetries which were considered in detail. They can be divided into two classes; those which affect e_{3n} in the same direction whatever the sign of θ_2 and those which affect e_{3n} in a way depending upon the sign of θ_2. The former affect the value of D, the latter the value of P_2'.

The energy of the polarized beam has a systematic variation totaling 5 Mev across the defining slit. This change gives a correlation of energy with angle in the second scattered beam. The alignment procedure takes no account of energy, but the cross section at the third scatterer varies with energy. A correction has been deduced from published cross-section data[13,14] and amounts to a reduction of D by 0.01 at most angles. This is always less than $\frac{1}{3}$ of the error.

A change in energy in the second scattering process alters e_{3n} in opposite directions as θ_2 is changed. Thus only P_2' is affected. The effect has been calculated and is negligible. The largest effect on the asymmetry is 0.0021 for $\theta_2=40°$. A change in second scattering cross section would cause the alignment profile to be asymmetric and would be corrected by our alignment procedure.

Spurious asymmetries would result due to excessive absorbers in the telescope coupled with energy variation across the third scatterer.[2] The absorbers used in this work were so chosen and checked[15] to assure us that no such error is present.

The variation of polarization of the beam across the defining slit appears only in the expression DP_1P_3; since D are shown to be small, small errors and variations in P_1 are of no consequence. Residual magnetic fields in the experimental area were a maximum of 10 gauss. These could cause an error in finding θ_3 by optical sighting of 0.025° at $\theta_2=40°$. This effect vanishes for the counter sweeping procedure.

It is possible that the polarized beam has components of polarization in the first scattering plane as well as perpendicular to it. If the centers of all the counters are on the same level, any effect due to this vanishes.[15]

THE EXPERIMENTAL APPARATUS

The experimental dimensions chosen for this work were similar to those adopted by Chamberlain *et al.*[2] They are given in Table I and some typical angular resolutions of this apparatus are given in Table II.

Carbon was chosen in all but one instance to be the third scatterer. Lithium of a comparable thickness (ρt) to the carbon scatterer was used in measuring D at $\theta_2=40°$. This was because lithium was found to have 20% higher analyzing power than carbon at the appropriate energy. If counting statistics alone is the criterion for choice of the third scattering angle θ_3, then $P_3^2(d\sigma/d\Omega)_3$ must be maximized. If the criterion is to

[15] C. F. Hwang, thesis, Harvard University, 1959 (unpublished).

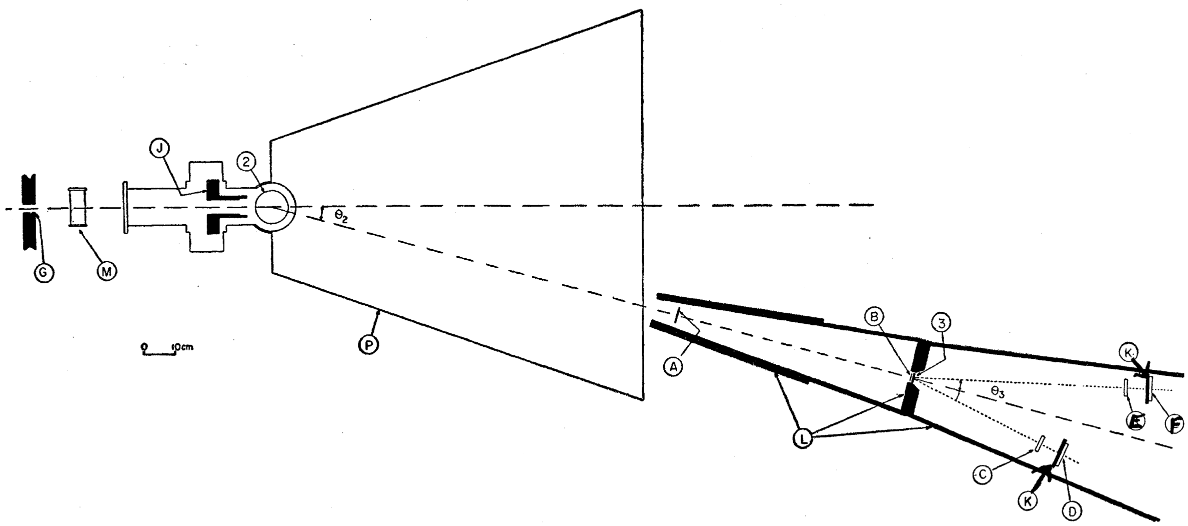

FIG. 3. Schematic diagram of the experimental arrangement for small angles ($\theta_2=6°$ to $15°$) showing: (2) hydrogen target, (3) analyzing scatterer, (*A-F*) scintillation counters, (*G*) main slits, (*J*) antiscattering slits, (*K*) copper absorbers, (*L*) iron shielding, (*M*) ion chamber, and (*P*) helium bag.

minimize the effect of misalignment, $P_3(d\sigma/d\Omega)_3/(d/d\theta)(d\sigma/d\Omega)_3$ must be maximized. 15° was chosen for all but one value of θ_2, and is close to the optimum for both criteria.

In order to accommodate all the mechanical motions of the counters necessary in the D measurement, a scattering table was constructed as shown in Fig. 1. It was pivoted at the front to provide the θ_2 motion and was mounted with three-point support so that it can be leveled without buckling even on the sloping floor. Fastened to this table were Counter A, the θ_3 pivot, counter B, the third scatterer, and various shieldings.

Riding on the θ_3 pivot, one on top of the other, were two telescope arms. Counters C, D were attached to the end of the upper arm, whereas counters E, F were located at a similar position on the lower arm. Each arm had its own leveling-screw arrangement located near the counters whereby each telescope could be brought to a level position whenever necessary. The arm and counters were so constructed that each one could be moved back and forth across the twice scattered proton beam without interfering with the other. Spirit levels were attached permanently at appropriate positions on the scattering table. Either telescope could be set at equal angles N and S of a nominal zero position by means of a sine bar.[15]

TABLE II. Typical angular resolutions.[a]

	The second scattering	
θ_2	Horizontal angular resolution	Vertical angular resolution
6°	1.5°	3.8°
20°	1.7°	6.9°
40°	3.2°	6.9°

	The third scattering ($\theta_3=15°$)	
Counter	Horizontal angular resolution	Vertical angular resolution
ABCD	6.6°	20.7°
ABEF	4.4°	13.8°

[a] All angular resolutions given are full width at half maximum.

To check the θ_2 pivot as a true mechanical pivot, a plumb line was placed directly over the pivot and the scattering table was leveled. An optical transit was mounted on the scattering table and sighted on this plumb line. The scattering table was then moved to 45° from this initial position on both sides, and the table was releveled. The line of sight of the optical transit was found to deviate no more than 0.02 cm from the plumb line at all times.

For small-angle measurements it was necessary to reduce background scattering. Modifications are shown in Fig. 3. The beryllium copper target cup was replaced by a 3-mil Mylar cylinder using the techniques developed at Illinois.[16] A bag made of zero-perm Mylar sandwiched aluminum foil was placed after the exit window and extended to Counter A. This bag was filled with helium to reduce scattering in the ratio $(\frac{1}{2})$ $(4/14)^2$ as compared to air.

At these small angles it was also necessary to keep all parts of the scattering table away from the polarized proton beam to avoid producing excessive neutron flux at the back counters and to prevent blocking the polarized proton beam to the Faraday cup. For this reason and also to prevent slit scattering, the entire third scattering arrangement (including counter B, the third scatterer, the back counters with their pivots, etc., and all the shielding) was translated as a unit 36 in. away from the hydrogen target. This translation

[16] V. O. Nicolai, Rev. Sci. Instr. **26**, 1203 (1956).

also improved the angular resolution of the second scattering. Counter B in this new configuration was 82 in. from the center of the hydrogen target, and Counter A was placed 30 in. in front of counter B. A 2 g/cm^2 carbon third scatterer was used for all small angle measurements. With these modifications, the quadruple coincidences for the small angles had a counting rate that was about one half of the corresponding large angle counting rate.

For the 6° point the Faraday cup was partially obscured and all monitoring was done with the ionization chamber. For this reason the results from the telescopes $ABCD$ and $ABEF$ were directly averaged and the higher statistical uncertainty used so that any monitor errors would directly cancel.

THE COLLECTION OF THE HYDROGEN DATA

e_{3n} was measured twice for each absolute value of θ_2, once with the protons scattered to the N of the polarized proton beam and once to the S. At a given θ_2, the back counters were aligned and e_{3n} measured. The back counters were reversed frequently so as to eliminate errors due to systematic beam monitor drifts. The third scatterer was reversed by rotating it 180° about its vertical axis after one half of the hydrogen data were collected. By so doing, any spurious asymmetries caused by non-uniformity of the third scatterer would be cancelled out automatically in the final data. The e_{3n} and P_1P_3 results obtained at these two orientations of the third scatterer never differed outside statistics. Random coincidences were also measured at the half way point.

After the completion of the e_{3n} measurements, the alignments of the back counters were checked, and the measurement proceeded to another value of θ_2. This process was continued until the hydrogen data for all the desired θ_2 values were completed. The remaining hydrogen was removed and the target was evacuated. The backgrounds were then measured for each θ_2, using the corresponding back counter alignment positions as determined in the e_{3n} measurements at that value of θ_2, and increasing the telescope absorbers as discussed below. The magnitude of backgrounds in the large-angle measurements were sufficiently small (about 3% of the e_{3n} counting rates) so that the error caused by measuring backgrounds at a later time would be negligible in comparison with statistical errors of the e_{3n} measurements. For the small-angle measurements, where the background is large, the background measurement immediately followed an e_{3n} measurement before the scattering table was moved.

To compensate for the difference in energy in the background measurements caused by the absence of the liquid hydrogen, extra absorbers equivalent to the range loss in the liquid hydrogen were added to the operating absorbers in the telescopes. It was not feasible to place these extra absorbers anywhere else without disturbing the energy and intensity distribution of the twice scattered proton beam and risking a change in the θ_3 alignments.

THE ANALYZING POWER P_1P_3

All values of P_1P_3 were empirically determined. The measurements of P_1P_3 were made with the scattering table set at $\theta_2=0$ position using reduced beam intensity, and the AB double coincidence counts as the beam monitor.

The matching of the mean third scattering energy for a given θ_2 simulation was achieved by shimming the beam energy to the desired value at the main slit. The details of this shimming process are given in reference 15. These shims also served the purpose of smearing the polarized proton beam so that the third scatterer was uniformly illuminated in the P_1P_3 measurements.

After the shims were determined, the back counters were aligned by the same method as in e_{3n} measurements and P_1P_3 asymmetries were measured with the back counters reversed every thirty minutes. Measurements were continued until about ten thousand quadruple coincidence counts were accumulated. The apparatus was then reshimmed for another θ_2, and the process repeated until all the necessary P_1P_3 asymmetries were measured.

There was no need to measure random coincidences because the neutron intensity was reduced with the polarized proton beam intensity by a factor 1000. (No background measurement was necessary for the reason already given.)

BEAM POLARIZATION

The beam polarization P_1 of this experiment was measured by performing double scattering experiments with the triple scattering apparatus. The number of protons scattered at 15° to the S and to the N were measured as well as the associated random coincidences and backgrounds. The asymmetry P_1P_1' was calculated from the relationship

$$P_1P_1'=[I(\mathrm{S})-I(\mathrm{N})]/[I(\mathrm{S})+I(\mathrm{N})], \qquad (12)$$

where P_1' is the polarization of protons scattered by carbon at 145 Mev and 15°, and $I(\mathrm{S})$ and $I(\mathrm{N})$ are the normalized counts produced by protons scattered to the S and to the N, respectively, corrected for random coincidences and background. The proton-carbon polarization measurements of Dickson and Salter[13] and Alphonce *et al.*[14] were plotted versus $\theta\sqrt{E}$, and P_1' was interpolated linearly in energy at constant $\theta\sqrt{E}$. By dividing out this interpolated P_1' from the measured asymmetry, one arrived at the value of 0.67 ± 0.02 for P_1. Palmieri *et al.*[7] employed the same procedure to obtain P_1 at 147.5 Mev. They found the value of P_1 to be 0.71 ± 0.02 because they used that portion of the polarized proton beam which had higher polarization.

CARBON D CHECK

It would be helpful to check the reliability of the experimental apparatus and procedures for the determi-

TABLE III Results of carbon D check. P_2 is the proton-carbon polarization measured by double scattering. P_2' is the proton-carbon polarization measured by triple scattering (see "Calculation of Results and Errors").

$D=1.032\pm0.064$
$P_2=0.458\pm0.027$
$P_2'=0.426\pm0.043$
$P_2=0.51\pm0.02$[a]
$P_2=0.518\pm0.025$[b]

[a] Proton-carbon polarization measured by Dickson and Salter (reference 13) at 135 Mev and 10°.
[b] Proton-carbon polarization measured by Alphonce *et al.* (reference 14) at 155 Mev and 10°.

nation of D by performing a measurement on a spin zero nucleus whose value of D is known to be unity. One must bear in mind, however, that such a check does not absolutely guarantee the validity of the hydrogen measurements. These checks cannot possibly duplicate all the conditions pertaining to the hydrogen scatterings since the energy and intensity distributions of the twice scattered proton beam illuminating the third scatterer would be different from those coming from proton-proton scattering.

D of carbon was measured at $\theta_2=10°$ following the procedures described in the section on "The Collection of the Hydrogen Data." 10° was chosen because the differential cross section of proton-carbon scattering at 142 Mev is relatively flat at this angle, hence the intensity distribution of the twice scattered proton beam across the third scatterer was minimized. The results of the carbon D check are given in Table III.

BEAM ENERGY

For the determination of the mean energy of the polarized proton beam, the range curves from hydrogen scattering at various values of θ_2 were used. Assuming a loss of about 5 Mev in the last crystal of the telescope (equivalent to approximately $\frac{1}{2}$ Mev of beam energy), the mean energy of the polarized proton beam was calculated from the empirically determined mean energy in the copper absorbers, for each hydrogen scattering angle. The copper range energy relationship of Rich and Madey[17] were used with ranges lowered by 1% to give agreement between their polyethylene and copper range at 140 Mev. The averaged value of the mean energy of the polarized proton beam was found to be 146 Mev, and the uncertainty in the calculation due to the uncertainty in the ranges was about 1 Mev.

The energy dispersion of the polarized proton beam is 5 ± 1 Mev/inch[10] found from the position of a beam scattered after a 2nd traversal through the first target. This agrees with the direct measurement of 4 Mev/inch by Cormack *et al.*,[18] for a beam size similar to that used in this work.

CALCULATION OF THE RESULTS AND ERRORS

Four sets of raw counts $I'(\theta_{2K},\theta_{3M})$ of the hydrogen data were obtained at a given θ_2. These raw counts are corrected for randoms $R(\theta_{2K},\theta_{3M})$ and backgrounds $BG(\theta_{2K},\theta_{3M})$ in the usual way to obtain the true counts $I(\theta_{2K},\theta_{3M})$. For $\theta_2=6°$ and 10°, besides performing the direct background subtraction, the measured backgrounds and background randoms were multiplied by the correction factors mentioned in the section "Backgrounds" before they were subtracted from the raw counts.

From the corrected counts, $e_{3n}(\theta_{2S})$, $e_{3n}(\theta_2N)$, and e_2 were calculated [see Eqs. (5), (9), (10)]. The error in asymmetries due to the misalignment of θ_3 was calculated and the correction applied to the value of e_{3n}. The spurious asymmetries due to the energy and angular effects were also calculated and corrected. Table IV shows a calculation sheet of the e_{3n} determination at an angle where the corrections were the largest.

The calculation of P_1P_3 was much like the calculation of e_{3n}. Since randoms and backgrounds were neglected, raw counts were used for the computation of the

TABLE IV. Typical e_{3n} calculations. A is the correction due to misalignment of θ_3 as given by counter sweeping; B is the correction due to spurious asymmetry from energy variation across the polarized proton beam; C is the correction due to spurious asymmetry from energy variation in the scattering process.

	$\theta_2=6°$N		$\theta_2=6°$S	
Measurement	Measured BG	Corrected BG	Measured BG	Corrected BG
$I'(\theta_2,S)$	0.442±0.011	0.442±0.011	0.678±0.014	0.678±0.014
$R(\theta_2,S)$	0.011±0.005	0.011±0.005	0 ±0.005	0 ±0.005
$BG(\theta_2,S)$	0.091±0.007	0.111±0.011	0.199±0.010	0.221±0.016
$R_{BG}(\theta_2,S)$	0.007±0.005	0.009±0.006	0.009±0.005	0.010±0.006
$I(\theta_2,S)$	0.347±0.015	0.329±0.017	0.488±0.019	0.467±0.023
$I'(\theta_2,N)$	0.541±0.012	0.541±0.012	0.587±0.013	0.587±0.013
$R(\theta_2,N)$	0.006±0.004	0.006±0.004	0.015±0.009	0.015±0.009
$BG(\theta_2,N)$	0.075±0.006	0.089±0.009	0.080±0.007	0.103±0.012
$R_{BG}(\theta_2,N)$	0.008±0.006	0.010±0.008	0.003±0.003	0.004±0.004
$I(\theta_2,N)$	0.468±0.015	0.456±0.017	0.495±0.018	0.473±0.020
e_{3n}	−0.148±0.026	−0.164±0.031	−0.007±0.026	−0.006±0.032
A	−0.009±0.001	−0.009±0.001	0.002±0.001	0.002±0.001
B	−0.003±0.001	−0.003±0.001	−0.003±0.001	−0.003±0.001
C	0	0	0	0
e_{3n}'	−0.161±0.026	−0.176±0.031	−0.008±0.026	−0.007±0.032

[17] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished).
[18] A. M. Cormack, J. N. Palmieri, N. F. Ramsey, and R. Wilson, Phys. Rev. **115**, 485 (1959).

TABLE V. Depolarization and polarization in p-p scattering at 142 Mev. (M) refers to measured background; (C) refers to corrected background. E_s is the mean energy of third scattering as given by the shims in Mev.

			D		P_2			
θ_2(lab)	θ_3	E_s	Harvard	Harwell	Harvard	Harwell	P_2'	P_3
6°(M)	15°	125	−0.234±0.049		0.147±0.026		0.143±0.034	0.440±0.024
6°(C)	15°	125	−0.262±0.063		0.144±0.029		0.159±0.045	0.440±0.024
10°(M)	15°	121	0.040±0.033		0.185±0.012		0.183±0.022	0.434±0.027
10°(C)	15°	121	−0.008±0.038		0.169±0.015		0.183±0.026	0.434±0.027
15°	12°	116	0.137±0.033	0.215±0.078	0.217±0.011	0.268±0.038	0.174±0.023	0.325±0.012
20°	15°	109	0.156±0.031	0.006±0.055	0.244±0.010	0.280±0.028	0.221±0.021	0.368±0.008
25°	15°	100	0.178±0.033	−0.195±0.061	0.231±0.010	0.211±0.027	0.168±0.022	0.310±0.012
30°	15°	94	0.076±0.031	−0.188±0.076	0.184±0.006	0.236±0.030	0.193±0.021	0.238±0.009
35°	15°	76	0.147±0.070	−0.396±0.154	0.114±0.010	0.66 ±0.027[a]	0.116±0.047	0.143±0.008
40°	15°	67	0.286±0.099		0.074±0.007		−0.009±0.066	0.088±0.011

[a] It is possible that this value was intended to be 0.066±0.027.

asymmetries. Corrections for misalignment of θ_3 were made as for e_{3n}.

For each value of θ_2, D and P_2' were calculated from Eqs. (7), (8), and (11). Calculating D by use of Eq. (7) has an additional advantage besides making D less sensitive to the values of P_1 and P_2'. If there exist some systematic asymmetries in the measurements which increase e_{3n}(S) and decrease e_{3n}(N), or vice versa, such spurious asymmetries would not cause any first order error in D by this method of analysis. Similarly, systematic errors which increase or decrease both asymmetries do not cause first order errors in P_2'.

At $\theta_2=6°$, because of the finite vertical angular resolution and the small nominal scattering angle, the tilting of the second scattering plane is more severe than at other hydrogen scattering angles. The values of D and P_2' have not been corrected for this effect. The correction is estimated to be not more than 6%.

The final errors quoted for the D results included the uncertainty due to misalignment, monitor drift, energy variation in the twice scattered proton beam, and counting statistics, with the counting statistics being the dominant factor.

THE FINAL RESULTS

Table V gives the final results of D, P_2, P_2' and P_3 of this work and the D and P_2 measured by Taylor and Wood[12] at 143 Mev. Figure 4 gives the graphic representation of D together with the results of Taylor and Wood[12] as well as the theoretical predictions of D at 140 Mev by Gammel and Thaler[19] and Signell and Marshak.[20] Figures 5 and 6 give the graphic representation of P_2 and P_2' as compared with the proton-proton polarization results of Palmieri *et al.*,[7] interpolated to 142 Mev. Figure 7 gives the graphic representation of P_3 as compared with the proton-carbon polarization at 15° by Dickson and Salter[13] and Alphonce *et al.*[14]

CONSISTENCY OF MEASUREMENTS

Of all the results in this work, measured at eight angles between 6° and 40° plus a repeat measurement at 30°, the two independent measurements obtained from $ABCD$ and $ABEF$ quadruple coincidences agreed within one standard deviation seven out of nine times for D, five out of nine for P_2', and six out of nine times for P_2. At no time was the disagreement greater than two standard deviations.

Another internal check was to compare the counts obtained by counters $ABCD$ with those of $ABEF$ at identical values of θ_2 and θ_3. The dependence of the ratio $ABCD/ABEF$ on the geometry of the third scattering arrangement was calculated to be 2.25 on the basis of solid angles alone. Because counters CD and EF accepted protons scattered at different angular ranges and because scattering cross section varied with angle, this ratio should actually be somewhat smaller than

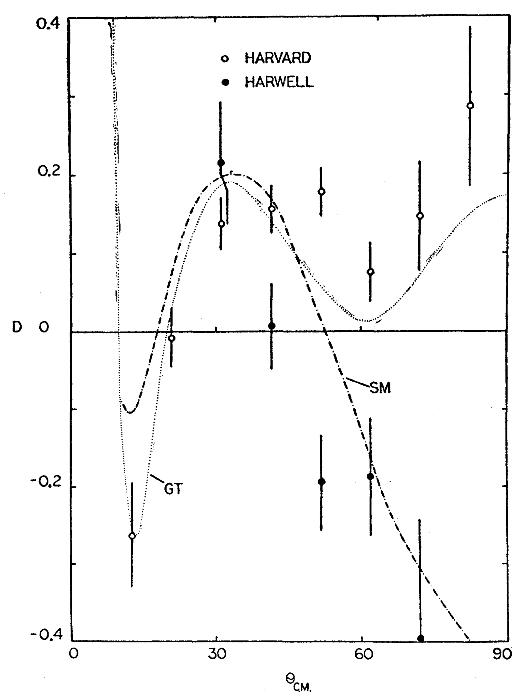

FIG. 4. D vs center-of-mass scattering angle, as measured by Taylor and Wood (reference 12) at Harwell and by the authors at Harvard, and as predicted by Gammel and Thaler (reference 19) and Signell and Marshak (reference 20).

[19] J. L. Gammel and R. M. Thaler, Phys. Rev. **108**, 163 (1957).
[20] P. S. Signell and R. E. Marshak, Phys. Rev. Letters **1**, 416 (1958).

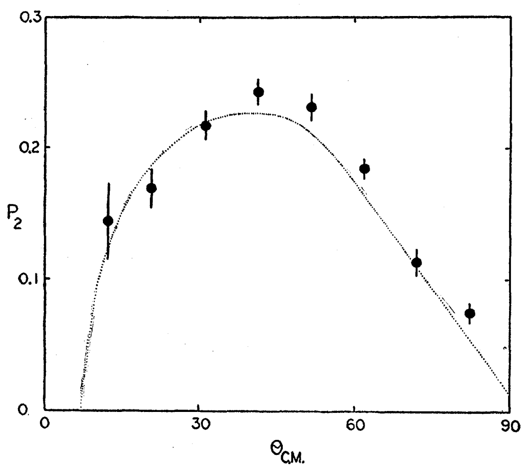

FIG. 5. P_2 vs center-of-mass scattering angle. The dotted curve represents the P_2 measurements of Palmieri *et al.* (reference 7), interpolated to 142 Mev.

this calculated value. It was measured to be 2.10 on the average with the points scattered about the average in a manner expected from statistics.

The P_2 and P_2' measurements were compared with the hydrogen polarization measurements of Palmieri *et al.*,[7] interpolated to 142 Mev. The agreements are good, although the P_2 from this work seem to show a tendency of being slightly higher than the results of Palmieri (see Fig. 5). The P_3 measurements were compared with proton-carbon polarization measurements of Dickson and Salter[13] and Alphonce *et al.*[14] at 15°. The agreement is good at mean energies of third scattering lower than 110 Mev, but the P_3 measurements of this work seem to be lower than those measured by other workers at mean energies of third scattering

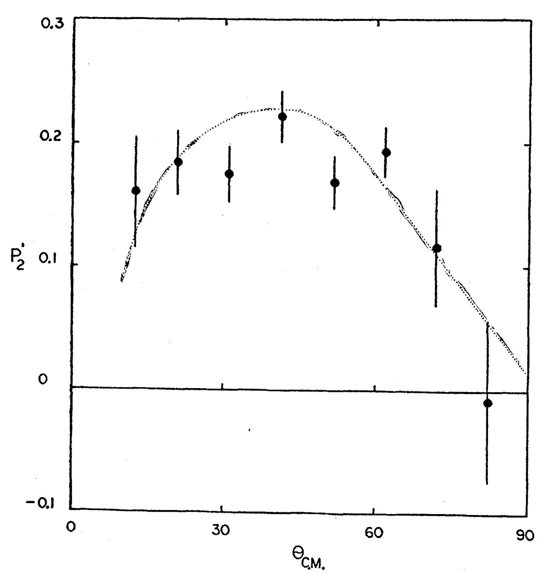

FIG. 6. P_2' vs center-of-mass scattering angle. The dotted curve represents the P_2 measurements of Palmieri et al. (reference 7) interpolated to 142 Mev.

higher than 120 Mev. This discrepancy can be attributed to two reasons. First, the measured P_3 included polarizations from the first two levels of proton-carbon inelastic scatterings which are lower than the polarization of the proton-carbon elastic scatterings.[13,14] Also, at energies in the neighborhood of 135 Mev, the reduction of the mean third scattering angle due to the cross-section change and poor angular resolution is of the order of $\frac{1}{2}$°, thus the mean polarization corresponds to protons scattered at $14\frac{1}{2}$° when the nominal θ_3 is 15°. This lower effective P_3 did not affect the results of this experiment for the reason that the values of $P_1P_3^*$ were empirically determined.

As explained in the section on "Alignment," the apparatus was aligned optically and small corrections made by the counter sweeping method. It is also possible to calculate all the values for D and P_2' using the best optical alignment. The results of this are shown in Table VI. The small differences are all attributed to residual errors in the optical alignment procedure.

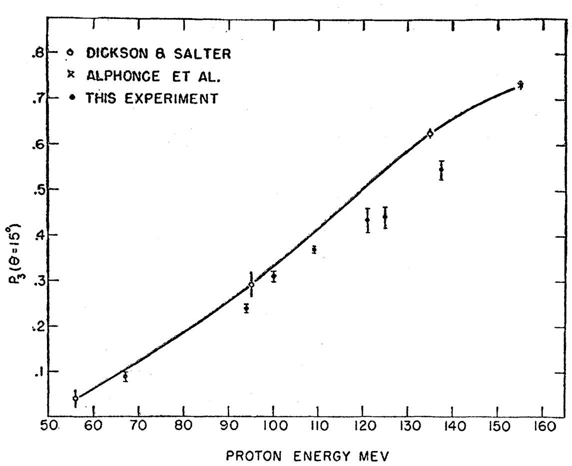

FIG. 7. Analyzing power P_3 vs energy E_3, of analyzing scattering. The 15° proton-carbon polarization values of Dickson and Salter (reference 13), and of Alphonce *et al.* (reference 14) are given for comparison.

COMPARISON WITH RESULTS OF OTHER LABORATORIES

The only other measurement of D in the energy range of this work was that by Taylor and Wood[12] at 143 Mev, performed at AERE, Harwell, England. Their results are given in Table V and Fig. 4. A brief glance at Fig. 4 is sufficient to tell that there is a major discrepancy between the two sets of data. Since the Harwell data were already reported just as this experiment was getting underway, the experimenters of this work were well aware of the discrepancy even in the very early stages of this experiment. Therefore, extreme care was taken throughout this work to search for all possible systematic errors introduced into the measurement either by the apparatus or through erroneous experimental procedures, and to correct them as they were discovered. No major error was ever found in spite of rather intensive effort and at no time in this experiment was D negative at large hydrogen scattering angles.

Since the Harwell experiment is not yet published and full details of their experiment are not available, it is difficult to make critical comparisons between the two experiments. However, based on the information provided by Taylor,[12] a comparison of some features of the two D measurements are given here.

Table I gives the comparison of the experimental dimensions. In general, the Harwell apparatus is smaller by a factor of 2.5. The Harvard experiment had three small causes of systematic errors not known to be present at Harwell via the energy and polarization change across the polarized beam, and a larger fringing field of the cyclotron. They are all discussed earlier.

The Harwell experiment has three separate possible causes of error not existing at Harvard. Firstly, the hydrogen target subtended a larger angle at the defining counter, making any resolution dependent correction quite large. There was no analog of the Harvard counter A, so that the Harwell experiment is sensitive to sources of background not present at Harvard. Thirdly, the Harwell experiment used an alignment procedure which is inferior and not capable of frequent repetition. In spite of these differences it is not possible to find, in detail, any source of error which is large enough to explain the discrepancy.

D has also been measured at 635 Mev by Kumekin *et al.*,[21] at 315 Mev by Chamberlain *et al.*,[2] and at 98 Mev by two of us.[8] The results at 315 Mev and 98 Mev show similar angular dependence to that given by this work.

TIME REVERSAL

The measurements of P_2 and P_2' constitute measurements of the time reversal invariance in the proton-proton interaction as suggested by Phillips.[22] In fact, the measurements of this work have the added advantage over other similar measurements[23,24] in that P_2 and P_2' are automatically measured at identical energies; hence direct comparisons are possible. Table VII gives the results of $(P_2'-P_2)$ from this work and compares them to the results of references 23 and 24. (Note that due to a difference in notations, P_2' and P_2 are equivalent to P and A, respectively, as given in references 23 and 24.)

TABLE VI. Effect of alignment method on D and P_2'.

	D		P_2'	
θ_2	Counter sweeping	Optical alignment	Counter sweeping	Optical alignment
20°	0.156±0.031	0.129±0.031	0.221±0.021	0.193±0.021
25°	0.178±0.031	0.184±0.031	0.168±0.022	0.123±0.022
30°	0.067±0.044	0.097±0.044	0.190±0.031	0.193±0.031
30°[a]	0.086±0.042	0.071±0.042	0.196±0.028	0.188±0.028
35°	0.147±0.069	0.081±0.069	0.116±0.047	0.067±0.047
40°	0.286±0.099	0.413±0.099	−0.009±0.065	−0.054±0.065

[a] Measurement from a preliminary run.

TABLE VII. Results of time-reversal invariance check. (M) refers to measured backgrounds; (C) refers to corrected backgrounds; c.m. refers to angle measured in the center-of-mass coordinate system.

θ_2	P_2'	P_2	$P_2'-P_2$
6°(M)	0.143±0.034	0.147±0.026	−0.004±0.043
6°(C)	0.159±0.045	0.144±0.029	0.015±0.054
10°(M)	0.183±0.022	0.185±0.012	−0.002±0.025
10°(C)	0.183±0.026	0.169±0.015	0.014±0.030
15°	0.174±0.023	0.217±0.010	−0.043±0.025
20°	0.221±0.021	0.244±0.010	−0.023±0.023
25°	0.168±0.022	0.231±0.010	−0.063±0.024
30°	0.193±0.022	0.183±0.006	0.010±0.023
35°	0.166±0.047	0.114±0.010	0.002±0.048
40°	−0.009±0.066	0.074±0.007	−0.083±0.066
30° c.m.[a]	0.279±0.017	0.308±0.005	−0.029±0.018
30.9° c.m.[b]	0.264±0.014	0.257±0.018	0.007±0.023
50.0° c.m.[b]	0.276±0.013	0.265±0.018	0.011±0.022

[a] Results according to Abashian and Hafner (reference 23).
[b] Results according to Hillman *et al.* (reference 24).

COMPARISON WITH THEORETICAL PREDICTIONS

Theoretical predictions of the depolarization in proton-proton scattering at energies near 150 Mev have been calculated by Gammel and Thaler[19] and by Signell and Marshak.[20] The results of both calculations are also given in Fig. 4. It is apparent that the results of Taylor agree closely with the predictions of Signell and Marshak, whereas the results of this work tend to substantiate the calculations of Gammel and Thaler.

The angular dependence of D is dictated by the range of the spin-orbit force through the $^3P_0$ phase shift. Thus it is possible to adjust the calculations of Signell and Marshak to fit both the 315-Mev results of the Berkeley group and the results of this experiment.[25] Furthermore, Gammel and Thaler[26] feel that in order to fit the D results of Taylor and Wood simultaneously with the 315-Mev results, a term of higher order in momentum than the linear $\mathbf{L}\cdot\mathbf{S}$ term must be included in the potential.

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