Polarization in 217-Mev *p-n* and *p-p* Scattering*

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In a continuation of a general study of the nucleon-nucleon interaction, the polarization in 217-Mev quasi-elastic *p-n* scattering from deuterium was measured by CD_2-C subtraction. These data cover the angular range 40°–120° (c.m. system) and are in fairly good agreement with the predictions of the phase-shift analysis of Breit *et al.* The polarization in elastic *p-p* scattering was measured in the angular range 30° to 90° (c.m. system) at an energy of 210 Mev using a liquid hydrogen target, and from 60° to 120° (c.m. system) at 217 Mev using CH_2-C subtraction. These two measurements are in agreement over their common angular range but differ somewhat from the earlier measurements of Baskir *et al.* The data are somewhat better fitted by the predictions of the boundary-condition model of Bryan, Saylor, and Marshak than by the latest phase-shift analyses of Stapp, Moravcsik, and Noyes, and of Breit *et al.* The polarization in 217-Mev quasi-elastic *p-p* scattering from deuterium was measured over the angular range 60° to 110° (c.m. system) by CD_2-C subtraction; these data agree with our elastic *p-p* polarization results within the statistical precision of the measurements (about 1.5%).

I. INTRODUCTION

ELASTIC nucleon-nucleon scattering at energies below the pion production threshold has been extensively investigated during recent years. The ultimate objective of this research is to determine unambiguously, under the usual assumption of charge independence of nuclear forces, the scattering matrix for each of the two nucleon-nucleon isotopic spin states. The *p-p* interaction has been studied far more thoroughly than the *n-p* interaction, first because the results give direct information on the isotopic triplet system, and second because *n-p* scattering experiments are more difficult to perform than the corresponding *p-p* experiments. The elastic *p-p* scattering experiments performed at this laboratory and reported in the literature include measurements of the differential cross section at 240 Mev,[1] the polarization at 130, 170, and 210 Mev,[2] and the triple scattering parameters *R*, *A*, and *D* at 213 Mev.[3,4] The interpretation of these data is not yet in completely satisfactory form, but has been much improved during the past year; both the predictions of the modified phenomenological potential model of Bryan et al.,[5] and the partial wave analyses of Stapp *et al.*[6] and of Breit *et al.*[7] are in good agreement with the experimental results at energies near 210 Mev. It appears that only slight improvements in the experimental and theoretical methods are needed to yield a unique and accurate set of phase shifts (or, equivalently, a unique scattering matrix) for the *p-p* system at this energy. In order to obtain similarly precise knowledge of the *n-p* interaction (and, by using the results of *p-p* scattering experiments, to obtain the scattering matrix for the isotopic-spin singlet system) one must perform a minimum of six independent scattering experiments covering the entire angular range,[8] or a larger number of experiments covering a limited angular range. Most of these experiments, particularly the triple scattering experiments, are very difficult with present techniques.

As has been recognized for some time, it is possible to circumvent some of the difficulties encountered in performing elastic *n-p* scattering experiments by studying instead the quasi-elastic scattering of protons from neutrons bound in deuterium. The principal advantages of this approach are these:

(1) The ultimate precision of such measurements is considerably higher than is possible in elastic *n-p* scattering experiments, because the polarized proton beams have a higher polarization and better energy definition than the best available polarized neutron beams.

(2) The measurements can be performed at the same energy at which *p-p* scattering experiments are performed, thus in one way simplifying the interpretation.

Unfortunately, however, the interpretation of quasi-elastic scattering experiments is much more difficult than for free nucleon-nucleon scattering, and no one has succeeded in rigorously relating the quasi-elastic scattering results to the free nucleon-nucleon scattering parameters. It is believed, however, that under certain conditions the quasi-elastic and elastic scattering processes are nearly identical. For example, Kuckes *et al.*[9] have made detailed measurements of the polarization in quasi-elastic *p-p* scattering from deuterium at 143 Mev and from 60° to 90° (c.m. system); within the

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[1] C. L. Oxley and R. D. Shamberger, Phys. Rev. **85**, 416 (1952); O. A. Towler, *ibid.*, 1024 (1952). Data renormalized by W. Hess, Revs. Modern Phys. **30**, 368 (1958).
[2] E. Baskir, E. M. Hafner, A. Roberts, and J. H. Tinlot, Phys. Rev. **106**, 564 (1957).
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[4] K. Gotow and E. Heer, Phys. Rev. Letters **5**, 111 (1960); K. Gotow, E. Heer, and B. Lobkowicz (to be published).
[5] D. P. Saylor, R. A. Bryan and R. E. Marshak, Phys. Rev. Letters **5**, 266 (1960).
[6] H. P. Stapp, M. J. Moravcsik, and H. P. Noyes (private communication).
[7] G. Breit, M. H. Hull, Jr., K. E. Lassila, and K. D. Pyatt, Jr., Phys. Rev. **120**, 2227 (1960).
[8] H. P. Stapp, Ann. Rev. Nuclear Sci. **10**, 292 (1960).
[9] A. F. Kuckes, R. Wilson, and P. F. Cooper, Jr. (private communication).

few percent statistical errors of the measurements, their data agree with the 143-Mev elastic p-p polarization data of Palmieri *et al.*[10] We have measured the quasi-elastic p-p polarization at 217 Mev by a method similar to that of Kuckes *et al.*, and have made two sets of elastic p-p polarization measurements. These measurements are described in this paper in Secs. II–IV; they also indicate that the elastic and quasi-elastic p-p polarizations are nearly equal. On the other hand, it appears from calculations by Phillips[11] that the polarization in quasi-elastic n-p scattering in deuterium at angles near 180° (c.m. system) differs somewhat from that found in free n-p scattering. One would, however, expect final-state interactions to be particularly important in this case, since the two protons are left after the collision with small relative kinetic energy. In view of the above considerations (and pending the development of a rigorous theory of the three-body interaction) we expect that the quasi-elastic scattering experiments will at least give results sufficiently close to those for elastic n-p scattering to be of use in the initial searches for a partial wave analysis in the isotopic singlet state. The results of these analyses will then be subject to correction when sufficiently accurate elastic scattering experiments are completed.

We describe in Sec. V of this paper the first in a series of experiments in quasi-elastic p-n scattering from deuterium, the measurement of the 217-Mev polarization at angles of 40° to 120° (c.m. system) in 10° steps. The measurements were performed by counting the proton and neutron recoils in coincidence, using CD_2 and CH_2 targets and taking the difference in yield. Similar experiments have been performed at Harvard at 143 Mev by Kuckes and Wilson[12] and at Berkeley at 310 Mev by Chamberlain *et al.*[13] Although p-n triple scattering experiments are in progress at this laboratory, the present experiment is the only one completed at this energy; it is thus premature to attempt an analysis of the type discussed earlier. Our results are compared in Sec. VI with predictions of Hull *et al.*,[14] which are based on phase-shift analyses derived from results at other energies.

II. ELASTIC p-p POLARIZATION—FIRST METHOD

The polarized beam, which is produced as shown in Fig. 1, has been described in detail previously.[3] The beam polarization is 0.89 ± 0.02, the mean energy at the point indicated by T_2 in the figure is 217 ± 2 Mev, and the maximum intensity at that point is about 10^8 protons per second in an area 2 cm wide by 7 cm high.

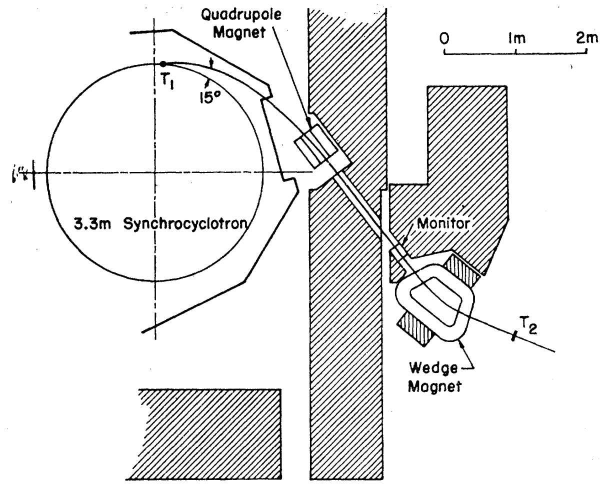

FIG. 1. Equipment for producing the 217-Mev, 89% polarized proton beam. The monitor is an air-filled ionization chamber. The experiments described in Secs. II, IV, and V were performed with the target at the position marked T_2.

An air ionization chamber which intercepts the polarized beam ahead of the wedge magnet is used as a monitor. The effective mean direction of the polarized beam at the target position was determined by a procedure similar to that used in earlier experiments.[3] The beam intensity distributions at T_2 and at a point P 195 cm further along the beam were measured by scanning the beam with a small scintillation counter telescope containing copper absorber. The beam axis was then defined to be the line passing through the centroid of the distribution at T_2 and a point displaced from the centroid of the distribution at P so as to correct for the bending of the protons in the magnetic fringe field of the cyclotron and bending magnets. Both the centroids at T_2 and P depend somewhat on the energy threshold set by the absorber in the scanning telescope. For example, the centroid at T_2 shifted by 0.5 mm as the minimum energy was increased from 100 to 185 Mev, and by 1 mm for an increase from 185 to 212 Mev. Thus there is some correlation of energy with position of the beam trajectories in the region of T_2, the significance of which will be discussed shortly. In order to align the second scattering apparatus, we chose a beam axis corresponding to an energy threshold of 185 Mev; this axis was preserved in space by means of an optical cathetometer.

For the measurement of elastic p-p polarization by the method described in this section, we detected in coincidence both recoil protons from CH_2 and C targets and computed the hydrogen yield from the difference in yield; both targets had an areal density of 0.12 g/cm² of carbon, and were normal to the beam axis. The mean energy of protons scattering in the center of the CH_2 target was 217 Mev. The second-scattering targets and detectors, which we shall call the polarimeter, were mounted on a horizontal table which could be rotated by 180° about a horizontal axis coinciding with the beam

[10] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and R. Wilson, Ann. Phys. 5, 299 (1958).
[11] R. J. N. Phillips, Proc. Phys. Soc. (London) 74, 652 (1959).
[12] A. F. Kuckes and R. Wilson, Phys. Rev. 121, 1226 (1961).
[13] O. Chamberlain, E. Segrè, R. D. Tripp, C. Wiegand, and T. Ypsilantis, Phys. Rev. 105, 288 (1957).
[14] M. H. Hull, Jr., K. E. Lassila, H. M. Ruppel, F. A. McDonald, and G. Breit, Phys. Rev. 122, 1606 (1961).

axis, thus interchanging "left" and "right" detectors. As is well known, this method minimizes spurious asymmetries resulting from errors in setting the included angle between detectors, inhomogeneous targets, and nonuniform counters. One proton was detected by a plastic scintillation counter 90 cm from the target, and the other by a triples scintillation telescope, the last counter of which was also 90 cm from the target. The dimensions of all four counters were approximately 5 cm×15 cm×0.6 cm, so that each detector had an angular acceptance of about 3° in the scattering plane; because of angular correlation effects, the angular resolution function for coincident protons was somewhat narrower. Except for the targets and the detector for the second proton, the experimental layout for this experiment was identical to that for the quasi-elastic *p-n* experiment; the layout for the latter experiment is shown in Fig. 2.

A copper absorber placed before the third telescope counter established the range threshold for one proton. The choice of this absorber thickness is dictated by two considerations: the dependence of effective misalignment errors on the range threshold, and the most desirable range threshold to be used in the quasi-elastic *p-p* scattering experiment. The relation of misalignment error to the range requirement stems from energy-position correlation of the beam in the target region. As explained above, the effective beam center at the target may shift by as much as 1.5 mm if one changes the energy threshold of incident protons from 100 to 212 Mev. If the beam were essentially monoenergetic, a shift of this magnitude would correspond to a spurious asymmetry of only 0.005. In our initial measurements of the asymmetry, we chose an absorber thickness for the polarimeter triples telescope corresponding to a minimum energy of approximately 212 Mev; the results showed deviations from the expected antisymmetry of the polarization about 90° (c.m. system) corresponding to a misalignment of approximately 10 times the amount

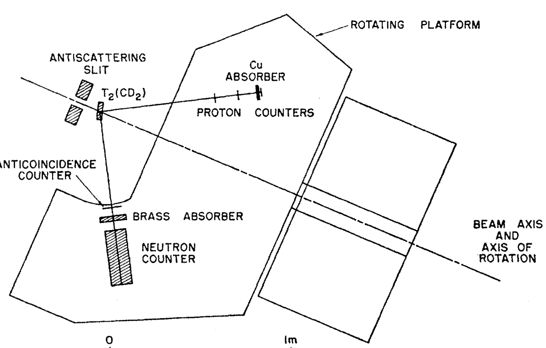

FIG. 2. Particle detectors, targets, and rotating table for quasi-elastic *p-n* polarization measurements. The antiscattering slit prevented the particle detectors from viewing the pole faces of the wedge magnet. For *p-p* polarization measurements the anti-coincidence counter, brass absorber, and neutron counter were removed and a thin scintillation counter was used to detect the recoil protons.

TABLE I. Polarization in *p-p* scattering.

θ	H_2 210 Mev	CH_2-C 217 Mev	CD_2-C 217 Mev
30°	0.312±0.009		
40°	0.319±0.011		
50°	0.303±0.010		
60°	0.240±0.009	0.246±0.010	0.222±0.014
70°	0.163±0.008	0.153±0.009	0.164±0.016
80°	0.084±0.007	0.079±0.008	0.098±0.014
90°	−0.002±0.007	0.014±0.011	0.000±0.014
100°		−0.090±0.009	−0.079±0.015
110°		−0.153±0.010	−0.155±0.015
120°		−0.218±0.011	

predicted above. This apparent contradiction was satisfactorily resolved by taking into account the energy-position correlation and the kinematics of *p-p* scattering, as explained below.

About 2–3% of the incident polarized protons have energy below 212 Mev; because of the dispersion of the wedge focusing magnet, these low-energy protons strike the target to the left of the centroid of the beam distribution. Thus a low-energy proton, in order to be detected in the triples polarimeter telescope, must scatter through a larger angle, and thus lose more energy, when the triples telescope is to the right than when it is to the left. If the range threshold established in the triples telescope is too high, the polarimeter will detect the low-energy component with much greater efficiency when it scatters to the left than when it scatters to the right; the resulting spurious asymmetry is much larger than that computed on the basis of the small shift in centroid of the entire beam. The only way to eliminate this effect is to set a sufficiently low range threshold; on the other hand, as will be discussed later, it is desirable to set the range threshold as high as possible in performing the quasi-elastic scattering measurements. Since we wished to select the same range requirement for all of the experiments, we made a series of elastic *p-p* asymmetry measurements at each angle to determine the dependence of the spurious asymmetry on the range threshold. It was found that, as the range threshold was increased, the asymmetry was constant within statistics until a certain thickness of absorber (which we call the critical absorber) was reached, beyond which the asymmetry changed rapidly; the direction of this change was correctly explained by the above considerations. The final data for this experiment and the quasi-elastic *p-p* and *p-n* measurements were taken with absorbers $\frac{1}{8}$-in. thinner than the critical absorber.

The electronic circuits were designed for both *p-p* and *p-n* scattering measurements; they are shown later in block form (see Fig. 5). Random coincidence rates (which in this case were no more than 0.5% of the true rates) were obtained by delaying the signal from one proton detector by one cyclotron rf period, or 50 nanoseconds (nsec), with respect to the signal from the other detector. The yield from carbon was at most 3% of the hydrogen yield. The asymmetry in scattering through angles of 60° to 120° (c.m. system) was measured to better than 1%. At angles less than 60°, and greater than 120°, an appreciable spurious asymmetry would be introduced by the deflection of the low-energy recoil proton between the target and the detector; in addition, for large angles, the critical absorber thickness could not be reached (i.e., the telescope itself would impose too severe a range requirement).

The results are listed in Table I. The angles listed there are the c.m. system scattering angles of particles accepted by the triples telescope. The errors quoted include only statistical errors and the uncertainty in the initial beam polarization. We believe the errors resulting from actual misalignment of the polarimeter and mechanical deformations contribute less than 0.004 to the asymmetry, while the possible error from the range threshold effect discussed above is less than 1%. Upon comparison of these results with those of Baskir *et al.*,[2] interpolated to the same scattering angles, we found substantial disagreement at 60° and 70° (c.m. system) angles. Although we were not able to explain this discrepancy, we noted that the methods used in the two experiments were different in several important respects. It therefore seemed worthwhile to perform additional measurements of the elastic p-p polarization in a manner similar to that used by Baskir *et al.* These are described in the following section.

III. ELASTIC p-p POLARIZATION—SECOND METHOD

In this arrangement, the second scattering target was a 9-cm diameter liquid hydrogen cylinder, and only one recoil proton was detected. As illustrated in Fig. 3, the polarized beam first passed through a $\frac{1}{16}$-in. lead scatterer, or diffuser, which was placed at the T_2 position of Fig. 1. A liquid hydrogen target was placed 125 cm from the diffuser. Protons of about 215 Mev suffered multiple scattering of about 2° rms in the lead diffuser; this effectively eliminated any correlation of direction or energy of protons with position at the hydrogen target position. The beam striking the target was defined by two slits, and the polarimeter detectors were protected from slit edge scattering by a wider third slit. The mean energy of protons scattering in the middle of the target was 210 Mev. In this case the polarimeter axis was aligned on the line passing through the geometrical centers of the two defining slits. After the asymmetry measurements were concluded, the centroid of the beam distribution at the position of the liquid hydrogen target was found to be displaced by 1.5 mm from the polarimeter axis. Most of this discrepancy was explained by the deflection of the beam in the fringe fields, and the resulting spurious asymmetry was calculated to be less than 0.004 at all angles. Instead of realigning the apparatus and repeating the experiment, we corrected the measured asymmetries for this small misalignment.

The hydrogen-scattered protons were detected by two identical triple scintillator telescopes placed at equal angles to the "right" and "left" on a horizontal table; the table could be rotated by 180° about a horizontal axis aligned with the beam axis. The third counter in each telescope was the defining one; it had dimensions 2.5 cm×10 cm×0.6 cm, and was at a distance of 120 cm from the target center. Copper absorbers were placed just before the defining counters; the absorber thickness at each angle was chosen to correspond to a point on the "flat" portion of the range curve for scattered protons. In this case, there was no reason to suspect any spurious asymmetries related to the range threshold of the detectors. The triple coincidences were formed in Garwin coincidence circuits,[15] and all types of random coincidence rates were negligible. Background scattering rates were measured by taking runs with the target empty; these rates as compared with the hydrogen scattering rate, were about 20% at 30° (c.m. system), 10% at 40° (c.m. system), and 7% at larger angles.

The net hydrogen yield was calculated from the difference of the target-full and target-empty rates. This is not strictly correct, since some of the empty target rate comes from particles which would have lost energy in the target, had it been full of hydrogen, and thus would not have been counted. We estimate, however, that the error in the asymmetry resulting from such an effect is less than 0.002. The asymmetry was computed from the counting rates of each telescope in the left and right position, and the two values, which always agreed within statistics, were averaged.

The results are listed in Table I and shown in Fig. 4; the indicated errors include statistical errors, uncertainty in the beam polarization, and a small estimated error to allow for instrumental uncertainties. It will be seen that the results for elastic p-p polarization as measured by this method and by the first method, de-

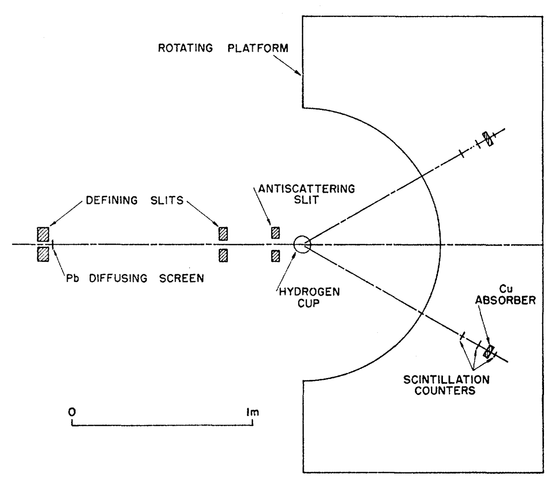

FIG. 3. Equipment layout for free p-p polarization measurements taken with a liquid hydrogen target.

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

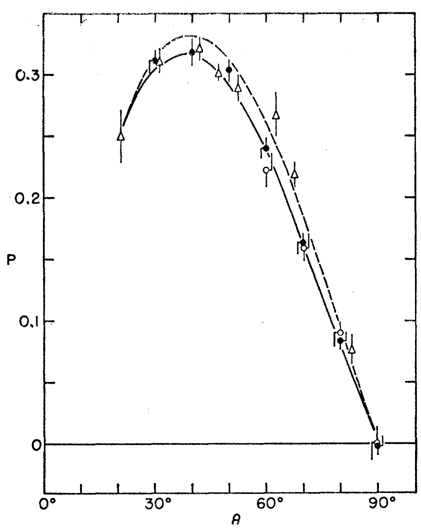

FIG. 4. Polarization in p-p scattering. The solid circles are 210-Mev free p-p data from a liquid hydrogen target, and the open circles are 217-Mev quasi-elastic p-p data from CD_2-C subtraction. The triangles represent the previous data of Baskir *et al.*[2] The dotted curve is an average of the predictions of the Livermore b phase-shift solution and the Yale YLAM solution[6,7]; these polarization predictions are nearly identical and are combined for clarity. Likewise, the solid line is an average of the Yale YRB1 and the Rochester[5] polarization calculations.

scribed in Sec. II, are in good agreement within the quoted errors. Although the measurements refer to slightly different energies (210 and 217 Mev), we expect from the calculations of Breit *et al.*[7] that the polarization should not differ by more than 0.007 at the two energies. Since this amount is smaller than the average errors, the agreement is to be expected.

IV. QUASI-ELASTIC p-p POLARIZATION

The polarization in quasi-elastic p-p scattering from deuterium was measured in nearly the same geometry as that described in Sec. II. Both recoil protons from CD_2 and C targets were counted in coincidence; both targets had areal densities of 0.12 g/cm^2 of carbon. One may predict the correlation angle between the two protons by assuming that the neutron (or "spectator" particle) is at rest after the collision, and by taking into account the binding energy of the deuteron; this angle is very nearly 86.5° at all scattering angles we investigated. We measured the angular correlation function by setting the angular position of the polarimeter triples telescope and varying the angle of the single-counter detector. Measurements were made with the triples telescope detector placed in the proper position for quasi-elastic scattering at 50° and 90° (c.m. system), and in both cases the correlation function was found to be approximately 10° wide and peaked near the expected included angle of 86.5°; the included angle between detectors was therefore set at this value throughout the experiments.

When one speaks of a quasi-elastic scattering event, one normally means an event in which the spectator particle has very much smaller recoil energy than do either of the other two particles. On any reasonable grounds, we expect such events to resemble the elastic scattering events more closely than those in which the spectator particle has relatively large energy; we therefore wished to choose the parameters of the experiment so as to favor their detection. The three-body kinematics are completely determined by specifying the scattering angles of any two particles and the energy of one of them. Thus, if one sets a lower limit on the energy (or the range) of one of the two recoil protons, one sets an upper limit on the energy of the spectator neutron. It then follows that the higher the range threshold set on one proton (in this case by the absorber in the triples telescope detector), the lower will be the maximum neutron recoil energy. As was mentioned earlier, we had already established upper limits on the allowable triples-telescope absorbers chosen so as to avoid introducing spurious asymmetries. An absorber $\frac{1}{8}$-in. less than the critical absorber (defined in Sec. II) corresponds to maximum neutron recoil energies ranging from 6 Mev at 120° (c.m. system) scattering angle to 12 Mev at 60°. These limits seemed reasonable, since at all angles the lower-energy recoil proton had at least six times the maximum energy of the spectator neutron. The measurements reported here were made using the same absorbers as were used in the p-p scattering experiments; several measurements were also made with less absorber, with no significant difference in results.

There are several possible causes of spurious counts other than random coincidences (3% of CH_2 yield) and carbon yield (15% of CH_2 yield). The most important ones are elastic p-d scattering, quasi-elastic p-n scattering, and scattering from the hydrogen in the CH_2 contamination of the CD_2 target. In this experiment the angular resolution of the polarimeter detectors was sufficient to exclude p-d elastic scattering events. The yield from quasi-elastic p-n scattering events contributed negligibly to the measured asymmetry since both detectors had very low neutron detection efficiency and the n-p and p-p asymmetries at this energy do not differ by more than 15% at any of the angles investigated. The scattering from the small CH_2 impurity (0.3%) is likewise of no consequence, since the elastic and quasi-elastic polarizations are known to be nearly equal.

The results, for c.m. system scattering angles of 60° to 120° taken in 10° steps, are tabulated in Table I. (The scattering angle corresponds to the position of the triples telescope for "ideal" quasi-elastic scattering, i.e., when the spectator particle has zero recoil energy.) It is seen that, within the experimental errors, the data are antisymmetric about 90° c.m. system), and are in agreement with the elastic p-p polarization data. The data are also shown on Fig. 4; here the points at 70° and 80° (c.m. system) are obtained by taking weighted averages of $P(\theta)$ and $-P(\pi-\theta)$.

V. QUASI-ELASTIC p-n POLARIZATION

The polarization in quasi-elastic p-n scattering from deuterium was measured using much of the same apparatus employed for the p-p scattering experiments. The proton and neutron recoil particles from CD_2 and C targets having areal densities of about 0.12 g/cm^2 of carbon were counted in coincidence; the difference in yield was attributed to scattering from the neutron. As shown in Fig. 2, the single-counter proton detector which was used in the experiments described in Secs. II and IV was replaced by an anticoincidence counter ($\bar{P}$), followed by a brass absorber, which in turn was followed by a large volume plastic scintillation counter designed for efficient neutron detection. The neutron counter scintillator was a cylinder of 11 cm diameter, and was either 30 cm long (for measurements at 60° or greater scattering angles) or 7.5 cm long (for measurements at 40° and 50° (c.m. system). The center of the scintillator was approximately 110 and 80 cm from the target in the case of the long and short counter, respectively. The scintillator was viewed by an RCA-7046 photomultiplier tube which was magnetically shielded by three concentric $\frac{1}{16}$-in.-thick mumetal shields extending 15 cm beyond the ends of the photomultiplier tube. This assured that the gain of the photomultiplier did not change by more than 2% when the polarimeter was inverted; the resulting spurious asymmetry due to change in gain was less than 0.004. The brass absorber placed just ahead of the neutron detector scintillator was chosen to be thick enough to stop at least 97% of the recoil protons from the target. The anticoincidence counter, a circular disk of scintillator 0.6 cm thick and 12.5 cm in diameter, had a counting efficiency for protons of better than 99.5%. The probability of counting protons was therefore expected to be negligibly small compared with the neutron counting efficiency. For experimental verification of this assumption, we observed that the apparent p-n coincidence rates from C and CH_2 targets were indistinguishable.

As in the p-p scattering measurements, the range threshold on the recoil proton was determined by choosing copper absorbers in the triples telescope $\frac{1}{8}$ in. thinner than the critical absorber thickness. As explained in Sec. IV, this established an upper limit on the spectator particle energy (in this case, the spectator proton). At proton scattering angles greater than 40° (c.m. system), the energy of either detected particle was at least six times the energy of the spectator proton, but at 40° (c.m. system), where the average neutron energy is approximately 25 Mev, it was just possible to detect events for which the neutron energy was only 4.5 times that of the spectator proton.

The electronics circuits are shown in block form in Fig. 5. A triple-coincidence signal was formed from the triples-telescope proton detector; this signal was then placed in coincidence with the neutron detector signal, and in anticoincidence with the counter $\bar{P}$ signal, using a fast Berkeley[16] coincidence circuit. The output signal of the Berkeley coincidence circuit opened a gate which passed the neutron counter signal, attenuated in attenuator A_N'. The gated signal was then applied to an integral pulse-height discriminator, whose output was counted. The setting of attenuator A_N' was chosen so that the threshold of the discriminator, rather than that of the Berkeley coincidence circuit, determined the minimum detected neutron counter pulse. Before taking data at each angle, the counting rate was measured as a function of the attenuation A_N. At all angles of scattering, we were able to find a range of values of A_N over which the counting rate varied by no more than about 2% per db change in attenuation. The attenuator A_N' was then set to a value in the middle of this range. Although, under these conditions, the counting rate was not sensitive to changes in gain of the neutron counter, we guarded against spurious asymmetry from change in gain by inverting the polarimeter at frequent intervals. We believe that no appreciable errors in the asymmetry were introduced by dead times, pile-up, or counting losses in the electronic circuitry.

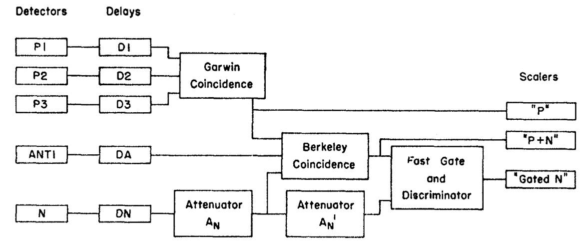

FIG. 5. Electronic circuits for p-n polarization measurement. For the p-p measurements the anticoincidence input was disconnected and the recoil proton counter pulses went into the delay box DN. All asymmetry data were computed from the "Gated N" rate.

Of all the possible forms of background, the only appreciable ones were random coincidences between the neutron detector and proton detector ($\leq 20\%$ of the CD_2 yield) and the carbon yield ($\leq 15\%$ of the CD_2 yield). The random coincidences were measured by counting with the neutron counter delayed relative to the proton detector by 50 nsec; since the cyclotron intensity was very stable during these runs, this subtraction method was quite satisfactory.

The p-n polarization data are presented in Fig. 6 and Table II. The results are for angles from 40° to 120° (c.m. system) scattering angles. The quoted errors included statistical errors, the uncertainty in the beam polarization, and an estimated error to account for alignment uncertainties.

VI. CONCLUSIONS

(1) It appears from Fig. 4 that our elastic p-p polarization data are in agreement with those previously

[16] University of California Lawrence Radiation Laboratory Report UCRL-3307 Rev., File No. CC3-9 (unpublished).

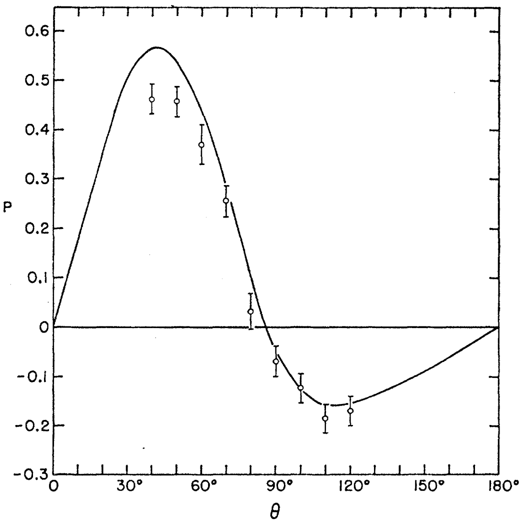

FIG. 6. Polarization in 217-Mev quasi-elastic *p-n* scattering from deuterium. The curve shows the polarization predicted by the phase parameter solution YLAN3 of the Yale group.[14]

reported by Baskir *et al.*[2] from 30° to 50° (c.m. system); near 60° and 70° (c.m. system) our polarizations appear to be significantly smaller than those measured by Baskir. We cannot explain the discrepancy, but believe that the present data are not substantially in error since they show zero polarization at 90° (c.m. system).

Figure 4 also shows the polarizations theoretically predicted by the Bryan-Saylor-Marshak[5] (BSM) boundary condition model, the Stapp-Moravcsik-Noyes[6] (SMN) phase shift solution, and the Yale[7] YLAM and YRB1 phase shift solutions. The BSM and YRB1 predictions give a good fit to our data, while the YLAM and SMN curves lie above our data near 60° and 70° (c.m. system). However, these phase shift solutions were computed before the present polarization data become available, and it is conceivable that small changes in the phase shifts might lower the polarization near 60° without altering the theoretical fit to the

TABLE II. Polarization in 217-Mev quasi-elastic *p-n* scattering from deuterium.

θ_p	P
40°	0.469±0.028
50°	0.460±0.031
60°	0.372±0.041
70°	0.258±0.033
80°	0.032±0.036
90°	−0.069±0.032
100°	−0.124±0.029
110°	−0.184±0.029
120°	−0.170±0.030

experimentally observed R, A, and D parameters at this energy.

(2) The quasi-elastic *p-p* polarization is equal to the elastic *p-p* polarization within the statistical error of approximately 1.5%; one may therefore hope that the elastic *p-n* polarization does not differ from the observed quasi-elastic polarization by more than our 4% statistical errors.

(3) In Fig. 6, the quasi-elastic *p-n* polarization data are compared with the theoretical polarization predictions of Hull *et al.*[14] The data appear to lie significantly below the theoretical curve at 40° and 50° (c.m. system) and slightly below it at larger angles.

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