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Depolarization in 212-Mev Quasi-Elastic *p-n* Scattering*

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The triple scattering parameter D for 212-Mev quasi-elastic p-n scattering from deuterium has been measured at c.m. angles of 40°, 50°, 60°, 70°, and 80°. Protons and recoil neutrons from a liquid deuterium target were detected in coincidence. The experimental results are compared with the theoretical predictions of Breit and co-workers.

I. INTRODUCTION

WE report in this paper the results of a measurement of the triple scattering parameter[1] D for quasi-elastic p-n scattering from deuterium at 212 Mev, at angles of 40° through 80° in the center-of-mass system (c.m.). This experiment is the second in a series of quasi-elastic scattering studies conducted at the University of Rochester at approximately this energy; the first was a measurement of the p-n polarization[2] at 217 Mev. As is discussed in reference 2, it is hoped that, when the p-n quasi-elastic scattering studies have been completed and their results combined with those for p-p scattering,[3–5] the partial-wave phase parameters for p-n scattering and the scattering matrix for the $T=0$ isotopic spin state can be uniquely determined at this energy.

Although the theoretical treatment of the elastic nucleon-nucleon scattering problem is in satisfactory form, no method has yet been developed which relates the quasi-elastic scattering parameters to the elastic nucleon-nucleon scattering parameters in a rigorous way. Therefore, it appears that one should carry out elastic n-p scattering experiments so that their theoretical interpretation should be unambiguous. Unfortunately, elastic n-p triple scattering experiments using presently available techniques are exeedingly difficult. The greatest problem is that of producing a neutron beam having high intensity, large polarization, and good energy definition. It is, however, reasonably easy to scatter polarized protons from the neutron bound in deuterium and to analyze the polarization of the scattered proton (p-n-p scattering); the experiment described here is of this type. It is also conceivable but more difficult to analyze the polarization of the recoil neutron (p-n-n scattering); no such measurements have been made as yet.

Because of the lack of a satisfactory theoretical treatment, it has been customary to treat the experimental results of quasi-elastic scattering experiments as though the scattering were really elastic (i.e., the effect of the spectator nucleon is completely neglected). Although this procedure is obviously incorrect, it appears that it may not be greatly in error if the spectator particle recoils with considerably less kinetic energy than that of the two detected particles. For example, recent experiments[2,6] have shown that the polarization in quasi-elastic p-p scattering under these conditions is nearly equal to that for elastic p-p scattering. Pending further refinement of the theoretical methods, therefore, we shall also compare our results with those computed for elastic scattering. At Yale, Hull *et al.*, have recently searched for sets of phase parameters which fit the elastic n-p differential cross-section data and the elastic and quasi-elastic polarization data below 400 Mev; they have found that only a few sets are allowed.[7] This group has also computed the value of the D parameter[8] in p-n-p scattering predicted by these sets of parameters. We shall show that, although the data obtained in this experiment agree fairly well with the predictions, they are not of sufficient precision to reduce the number of permissible sets.

II. GENERAL EXPERIMENTAL METHOD

This experiment was carried out by the usual method of subjecting an unpolarized beam of protons to three coplanar scatterings. We reproduce the well-known relations describing the measurement of the D parameter for the second scattering,

$$D=\frac{1\pm P_1P_2}{P_1P_3}\epsilon\mp\frac{P_1P_2}{P_1^2}, \quad (1)$$

where P_i is the polarization which would be produced in an initially unpolarized beam when scattered under the conditions of the ith scattering. The upper signs in Eq. (1) are used when both first and second scatterings are in the same direction (e.g., both are left

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scatterings), while the lower signs are used for the opposite case. The asymmetry ϵ in the third scattering is defined by the equation

$$\epsilon = \pm (L-R)/(L+R), \tag{2}$$

where L and R are the intensities for third scattering to the left and right of the second scattered beam; the $+$ $(-)$ sign in Eq. (2) is used when the first scattering is to the left (right).

The experimental layout is shown in Fig. 1. The cyclotron circulating beam was scattered from an internal carbon target at 14.5°, emerged with a transverse polarization P_1 of 0.89 ± 0.02, and was brought to an approximate focus 75 cm beyond the last focusing magnet. The mean direction of the beam and its effective center (denoted by T_2) were determined as in previous experiments[4,5]; its mean energy was 217 ± 2 Mev, and the spread in energy was about 7 Mev. The beam entered a liquid deuterium cup which was a cylinder 12.7 cm in diameter and 10.2 cm high centered on T_2 with its axis vertical. The deuterium target was of conventional vacuum-jacket design; the cup had cylindrical walls of 0.013-cm Be-Cu, and the vacuum jacket windows were of 0.005-cm stainless steel. Since the energy loss of protons in the deuterium was about 10 Mev, the mean energy of scattered protons was about 212 Mev, with a total energy spread of about 17 Mev. A quasi-elastic p-n scattering event was identified by detecting the proton and neutron in coincidence; the proton was detected by a double scintillation counter telescope (counters 21 and 22), and the neutron was detected by a large-volume liquid scintillator (counter N). The included angle between the centers of these detectors was set at 86.5°; this is the approximate correlation angle between the two detected particles from a quasi-elastic collision in which the spectator particle is left at rest.

The second scattered protons were scattered again by a carbon target and detected by two identical triple scintillation counter telescopes set at equal angles to the left and right of the second scattered beam axis. The target T_3 and the two triple counter telescopes make up the polarimeter. This instrument was used by England *et al.*[4] (EGGHT) in a measurement of the p-p triple scattering parameters R and A and is described in detail by these authors. In the present experiment, as in the measurement of D for elastic p-p scattering by Gotow, *et al.*[5] (GHL), the polarimeter was mounted on a base frame which was pivoted about a vertical axis passing through T_2; this made it possible to change the angle of second scattering, and to change from right to left second scattering, without disturbing the alignment of the polarimeter. Upon changing scattering angles the neutron counter was lifted and repositioned to maintain the correct included angle. The angular resolution function, which was determined by the irradiated volume of the deuterium and by the polarimeter slit S_{24}, had a full width at half-maximum which varied from 2.1° at 40° c.m. to 2.9° at 80° c.m. scattering angles.

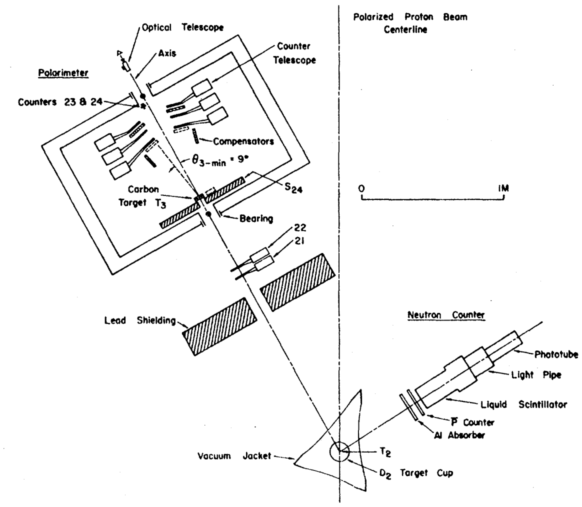

FIG. 1. Experimental layout for $D(\theta)$ measurement.

The neutron counter (N) was constructed so that the effective detector volume was variable. The basic scintillating unit was a tank of dimensions 20 cm diam by 15 cm long; its center was placed about 1.0 m from T_2. The sensitive volume could be increased by bolting on additional 15-cm diam tanks of different lengths; the added sections were attached to the front of the basic cylinder. The scintillation solution contained 5 g p terphenyl and 0.5 g POPOP per liter of sulfur-free toluene. The optimum length of such a counter is approximately equal to the absorption length for neutrons; for toluene, this length varies from approximately 20 cm for scattering at 40° c.m. to 90 cm for scattering at 80° c.m. Since a counter of the latter length would be unwieldy, the total length of scintillator used was 23 cm at 40° c.m., 31 cm at 50° c.m., and 41 cm at 60°, 70°, and 80° c.m. Light was conducted from the liquid scintillator to an RCA 7046 photomultiplier tube by a nonscintillating light pipe, 15 cm in diameter by 15 cm long, made of pure toluene. The inside surfaces of the tanks containing the light pipe and scintillating solution were painted with a diffusely reflecting white paint, and the photomultiplier tube was magnetically shielded by three concentric cylinders of $\frac{1}{16}$-in. mu-metal extending 15 cm beyond each end of the tube.

In order to avoid the detection of charged particles, an aluminum absorber, followed by an anticoincidence counter ($\bar{P}$) was placed between the deuterium target and the neutron counter. For each angle of scattering, the absorber thickness was chosen so that it stopped essentially all quasi-elastic recoil protons from deuterium. The anticoincidence counter, whose diameter was 20 cm, shielded the neutron counter from the irradiated volume of the target. The counting rates 21-22-N with and without anticoincidence differed by a few percent at most; thus the number of elastic p-d and quasi-elastic p-p events which were detected with the anticoincidence effective were quite negligible.

III. POLARIMETER ALIGNMENT

As is true in most polarization experiments, the central problem in this experiment was that of minimizing spurious asymmetries of geometric origin. The procedures used to determine the effective second scattered beam axis, and to align the polarimeter upon this axis, were based upon the results of the detailed studies of EGGHT and GHL. These authors investigated two nearly equivalent alignment methods. In the first method, the second scattered beam axis was defined to coincide with the trajectory of a proton which passed through the centroid of the beam intensity distribution at the second scattering target and through the center of the polarimeter slit S_{24}. The slight curvature of the trajectory in the cyclotron fringe field was taken into account, and the polarimeter axis was placed tangent to the trajectory at the third scattering target. In the second method, the polarimeter was aligned on the line passing through the center of slit S_{24} and the center of the measured intensity distribution of the second scattered protons at a distance of 80 cm beyond the slit. (The effect of the fringe field was negligible in this case.) The alignment positions indicated by the two methods, if expressed in terms of the angle of rotation of the polarimeter about a vertical axis through T_3, agreed to within 3 minutes of arc. The asymmetry produced by a rotation of this type was found to be about 0.002 per minute of arc, so that the maximum uncertainty in the measured asymmetries arising from misalignment of this type was taken to be 0.006.

In determining the second scattered beam axis for the present experiment on quasi-elastic scattering, one must take into account only the distribution of second scattered protons which are in coincidence with recoil neutrons. Therefore, in our preliminary runs, an adaptation of the second method was used; a coincidence was formed between counters 21, 22, N, and two search counters, 23 and 24, placed near the rear of the polarimeter (see Fig. 1). An absorber placed between 23 and 24 set the same range threshold as was set by the polarimeter in third scattering. The centroid of the intensity distribution measured by scanning the second scattered beam with the search counters was then taken to define the center of the beam. This procedure was found to be of limited accuracy because of the very small fivefold coincidence rates; the alignment position deduced in this way had an uncertainty of as much as 5 min of arc (in terms of the angle defined above). Within this uncertainty the alignment agreed with that obtained by the much simpler first method described in the preceding paragraph. The first method was therefore used throughout the experiment,[9] and an uncertainty of 0.01 was included in the asymmetries to account for the maximum expected error in alignment. Since the statistical errors in the asymmetries were more than 0.03 for all angles investigated, this procedure appeared to be adequate.

IV. POLARIMETER ANALYZING POWER

At each second scattering angle, the polarization in third scattering depends upon the energy of protons incident upon the third target and the energy detection threshold of the polarimeter triples telescopes; this threshold is determined by the thicknesses of the third target and the triples telescope absorbers. GHL had previously measured P_1P_3 by measuring the scattering asymmetry with the polarimeter centered on the polarized proton beam. For every combination of T_3 and absorber used during the D measurement, they measured the asymmetry with several different Pb degraders placed at the T_2 position; in this manner, P_1P_3 was measured as a function of the energy of protons incident upon T_3. Thus, at each scattering angle, they interpolated to find the correct P_1P_3 for the measured mean energy of the hydrogen-scattered protons. The range curves of the Pb-degraded and hydrogen-scattered protons had roughly the same shape, implying that the energy distributions of the two proton beams were similar.

For each second scattering angle, θ_2, we used the same T_3 and one of the absorbers (their absorber 2A) used by GHL. However, the shapes of the range curves of protons quasi-elastically scattered from deuterium were found to differ appreciably from those obtained by GHL for their Pb-degraded and hydrogen-scattered beams; the mean energy of deuterium-scattered protons was lower, and the spread in energy was larger, than was the case for hydrogen-scattered protons. Nevertheless, we chose the value of P_1P_3 interpolated from the data of GHL to an energy equal to the mean energy of deuterium-scattered protons. Since this is a somewhat questionable procedure, we have assigned an uncertainty in P_1P_3 corresponding to an uncertainty in the range of the scattered protons equal to the half-width at half-maximum of the differential range curve. Even though this assignment probably overestimates the error in P_1P_3, it contributes very little to the resulting error in the D parameter.

V. BACKGROUND SUBTRACTION

In order to obtain the net scattering yield from deuterium one could measure and subtract the yield from the empty target and the air in its vicinity.

[9] Actually the polarimeter axis was aligned with the effective beam center T_2, and the observed asymmetries were corrected for the effect of the deflection of the second scattered protons in the cyclotron fringe field. The resulting changes in the computed values of D were considerable smaller than the statistical uncertainties.

However, in the course of the quasi-elastic p-n polarization study,[2] it was found that the p-n quasi-elastic scattering cross section for carbon was much smaller than that from deuterium; this suggested that the empty deuterium target yield would be so small that it could be neglected entirely. In order to verify this, we performed the following tests: At 40°, 60°, and 80° c.m. an 0.6-cm Cu plate was placed normal to the beam at the T_2 position and the quasi-elastic scattering yield was measured under the same conditions used for the deuterium measurements. This plate had 12 times the combined thicknesses of the deuterium cup and vacuum jacket walls, so that the empty target yield was much enhanced. The yield from the copper was found to be very small and, within the errors, consistent with zero. From these observations, we estimated that any quasi-elastic scattering yield from the empty target walls would, within a 90% confidence limit, produce an error in D less than ± 0.02 at 80° and ± 0.01 at other angles; the error in D caused by the air scattering yield, estimated by taking the N and O cross sections equal to the known upper limit on the C cross section, was less than ± 0.002. Since the statistical uncertainties in D were approximately 0.10 or more, the empty target rates were considered to be negligible, and no attempt was made to subtract them from the observed counting rates with the second target full of deuterium.

VI. ELECTRONICS

An acceptable quasi-elastic scattering event was defined by the threefold coincidence 21-22-N in anticoincidence with $\bar{P}$. This signal, which we designate by $2P$, was then placed in coincidence with the triple coincidence signals from the two polarimeter telescopes to form the right and left triple scattering rates RP and LP. We expected that the only appreciable random coincidence rate would be that corresponding to random coincidence between a proton detected by the polarimeter and a signal in the neutron counter. In order to measure this rate, a second circuit was used to form a coincidence between 21-22-$\bar{P}$ and counter N delayed by 100 nsec from the proper value (two cyclotron rf periods). This signal, designated by $2D$, was then put in coincidence with the polarimeter telescope signals to form the random triple scattering rates RD and LD.

The dependence of the counting rates LP, LD, RP, and RD on the setting of the neutron counter gain was investigated. Since one detected in counter N pulses from recoil protons of widely different energies, the pulse-height spectrum deduced from these measurements had no plateau. For a certain range of the gain of counter N, it was found that the prompt and random rates varied with the gain in such a way that the statistical uncertainties in the net counting rates were almost independent of the gain setting. The gain was therefore set to a value at which the variation of counting rate with gain was a minimum; we were able in all cases to find a setting at which the counting rates changed by less than a factor of two for a 6-db change in gain.

It was found that under these conditions the random coincidence rates obtained at maximum cyclotron beam intensity were excessively large at the smaller scattering angles; this was due to the decrease in neutron energy and the increase in the proton rate with decreasing scattering angle. When necessary, therefore, the cyclotron beam intensity was reduced to a value such that the random rates were not more than about half the net prompt rates. The random and total coincidence rates were measured simultaneously to avoid errors in subtraction caused by beam intensity fluctuations. In order to correct for a difference in the resolving times of the $2P$ and $2D$ circuits, the prompt and delayed neutron counter input signals to the two circuits were periodically interchanged, thus interchanging the roles of coincidence circuits LP and LD, and of RP and RD. As in previous work,[4] the net triple scattering rates were obtained by taking the difference in yield with the third scattering target T_3 in and out (and compensating Lucite absorbers out and in; see reference 4). The yield of triple scattered protons was measured both with the polarimeter in its normal position and with it rotated by 180° about the polarimeter axis; in this way, two independent measurements of the asymmetry were computed from the counting rates obtained by the two telescopes. The duration of one cycle, comprising a run in which all the above variables were permuted, was two hours or less in all cases; the variables were permuted frequently in order to minimize the probability of introducing spurious asymmetries due to changes in photomultiplier gains and drifts in the electronic circuits. Each measurement of D at one angle was obtained by combining the data obtained from 10 to 50 cycles.

VII. *P-P* TRIPLE SCATTERING

By removing the Al absorber and replacing the N counter signal by the $\bar{P}$ signal, one could use the same apparatus for measuring the D parameter in p-p scattering. We originally hoped to measure D for quasi-elastic p-p scattering from deuterium and to compare the results with the elastic p-p measurements of GHL. However, at most scattering angles, the liquid deuterium target used in p-n studies was so thick that, if it were used for p-p scattering, the low-energy recoil proton would be stopped or badly scattered in the target; it was also not practical to make this measurement using CD_2 and C second targets of small stopping power because of the very low quasi-elastic counting rates. D was measured for elastic p-p scattering at 60° c.m., using CH_2 and C second scattering targets which had equal carbon content; the areal density of hydrogen was about 0.8 g-cm^{-2}. The high-energy proton (scattered at 28.7° lab) was detected and scattered in the

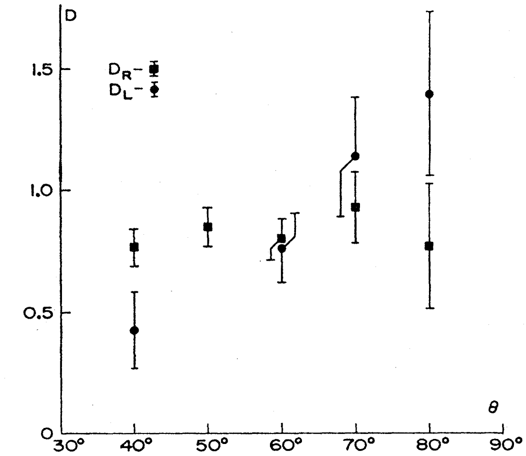

FIG. 2. Measured D_L and D_R values, corresponding to observations made for second scattering to left and right of polarized proton beam.

polarimeter, while the low-energy proton was detected by the $\bar{P}$ counter. The resulting value of D (0.40 ± 0.07) agrees satisfactorily with the GHL value of 0.33 ± 0.03; this indicates that, to this accuracy, our alignment procedure was adequate.

VIII. *p-n* SCATTERING RESULTS

Equation (1) shows that two separate determinations of D (which we call D_L and D_R) may be made by studying second scattering to both the left and right. It is desirable to make both of these determinations since, if D_L and D_R are found to be equal within the experimental errors, one may infer that the experiment is free from certain types of systematic errors. We measured the asymmetry for quasi-elastic *p-n* scattering at 40°, 60°, 70°, and 80° c.m. left and right scattering angles; for lack of time, the asymmetry at 50° c.m. was measured only for right scattering. The resulting values of D_L and D_R were computed and are shown in Table I and Fig. 2. The value of P_1 used in this computation was that determined by Baskir *et al.*,[3] while the values of P_1P_2 were those measured by the present authors for quasi-elastic *p-n* scattering[2] at 217 Mev. As explained in Sec. IV, we used values of P_1P_3 obtained by interpolating measurements of GHL to the appropriate mean energy at third scattering.

The asymmetry was measured with about the same statistical accuracy for left and right scattering. One sees from Eq. (1) that the error in the asymmetry is multiplied by the factor $(1\pm P_1P_2)$, which is smaller for right scattering; therefore the error in D_R is considerably smaller than that in D_L at angles where P_2 is large. One may combine D_L and D_R to find a mean value, $\bar{D}$. Merely taking a weighted average of these quantities gives an incorrect estimate of the probable error, since the errors in P_1, P_1P_2, and P_1P_3 are common to both left and right determinations of D. A somewhat preferable procedure is to combine the measurements

TABLE I. $D(\theta)$ for quasi-elastic *p-n* scattering at 212 Mev. D_L and D_R were combined to form the most probable values $\bar{D}_3$ and $\bar{D}_4$ using the procedures described in connection with Eqs. (3) and (4) of the text.

θ	D_L	D_R	$\bar{D}_3$	$\bar{D}_4$
40°	0.42 ± 0.16	0.76 ± 0.08	0.70 ± 0.07	0.71 ± 0.07
50°	···	0.85 ± 0.08	0.85 ± 0.08	0.85 ± 0.08
60°	0.76 ± 0.15	0.80 ± 0.09	0.79 ± 0.07	0.79 ± 0.08
70°	1.14 ± 0.25	0.93 ± 0.15	0.97 ± 0.14	0.99 ± 0.14
80°	1.39 ± 0.34	0.77 ± 0.26	0.98 ± 0.45	1.05 ± 0.45

with a weighting factor η which is regarded as a parameter in the equation

$$\bar{D}=(D_L+\eta D_R)/(1+\eta). \tag{3}$$

We then minimize the error in $\bar{D}$ with respect to η. In an alternative approach, we note that the two equations contained in Eq. (1) may be used to convert the measured left scattering asymmetry ϵ_L into an equivalent right scattering asymmetry ϵ_R'; the appropriate equation is

$$\epsilon_R'=\frac{(1+P_1P_2)}{(1-P_1P_2)}\epsilon_L-\frac{2(P_1P_2)(P_1P_3)}{(1-P_1P_2)P_1^2}. \tag{4}$$

$\bar{D}$ is then computed from the weighted average of ϵ_R and ϵ_R'. The results of the latter two methods, which we designate $\bar{D}_3$ and $\bar{D}_4$, are shown in Table I. They differ by amounts which are much smaller than the statistical uncertainties.

Although the values of D_L and D_R agree quite well for angles of 60° and 70° c.m., they disagree by 1.9 standard deviations at 40° and 1.4 standard deviations at 80°. One may question whether these deviations are caused by systematic errors or by statistical fluctuations. GHL, in measuring D for elastic *p-p* scattering at this energy, found a large difference between D_R and D_L at 90° c.m. (the difference was 0.4 ± 0.1) and a smaller discrepancy at 80°. Their discrepancy at 90° was clearly not of statistical origin, and therefore must have resulted from an unidentified systematic effect. If this effect causes the discrepancy to increase with decreasing second scattered proton energy, as is suggested by their observation that the discrepancy increases with increasing second scattering angle, the effect may be somewhat more important in the quasi-elastic scattering experiment, since the average energy of quasi-elastically scattered protons is lower than that of elastically scattered protons. We therefore suspect that our 80° data may contain systematic errors whose size is comparable to the statistical errors, and the error on $\bar{D}$ at 80° has been doubled to encompass the uncertainties in D_L and D_R. Since our experiment is very similar to the GHL experiment, and since they obtain agreement between D_L and D_R at angles less than and equal to 70° c.m. with much better statistical accuracy than was achieved in the present experiment, we believe that our 40° discrepancy is the result of a statistical fluctuation.

IX. DISCUSSION AND CONCLUSION

The weighted average $\bar{D}_4$ listed in Table I has been plotted in Fig. 3 along with the predictions obtained from two of the six sets of phase parameters proposed by the Yale group[7] to explain p-n cross section and polarization measurements at energies of 400 Mev and less; at the angles at which our measurements were made, the predictions obtained from the other four sets lie between the two theoretical curves shown in Fig. 3, and these four curves have been omitted from the figure for clarity. Our data, particularly those at 40° and 60° c.m., appear to favor the set of phase parameters YLAN2M over the set YLAN3M. There are, however, several reasons why this point should not be overemphasized. First, the largest discrepancy between the data and curve YLAN3M occurs at 40°, where we suspect that an unusually large statistical fluctuation has occurred in one of the measurements D_L and D_R. Second, it may be possible to make small changes in the YLAN3M phase parameters which would lower the predicted D at these angles without substantially altering the fit to the p-n differential cross-section and polarization data. Finally, we note again that the theoretical predictions are computed for elastic scattering, and that we do not know what deviation from our quasi-elastic results may be expected. We therefore cannot definitely conclude that this experiment has reduced the number of allowable sets of phase parameters.

As discussed in the introductory section, we plan to continue our quasi-elastic scattering studies at this energy; in particular, we hope to obtain improved data for the parameter D and also to measure other triple scattering parameters in experiments of the p-n-p type. Although one might consider extending the angular range and improving the precision of the measurements of D reported here, such improvements are not likely with present experimental techniques. The statistical accuracy in the present experiment is limited by the available beam intensity and the polarimeter analyzing power at large scattering angles, and by high random coincidence rates at low scattering angles. Furthermore, the discrepancy between D_L and D_R at 80° c.m. suggests that measurements at larger angles would be unreliable. We therefore do not expect to achieve much improvement by repeating the measurements with longer counting times. We expect in the near future to improve the energy definition of the polarized proton beam and to increase both the intensity and the effective duty cycle of the synchrocyclotron. It is hoped that these advances will allow us to design an improved experiment. However, it is probable that a more complete theoretical understanding of quasi-elastic scattering and measurements of other triple scattering parameters will be necessary in order to determine uniquely the p-n scattering phase parameters and the $T=0$ scattering matrix at this energy.

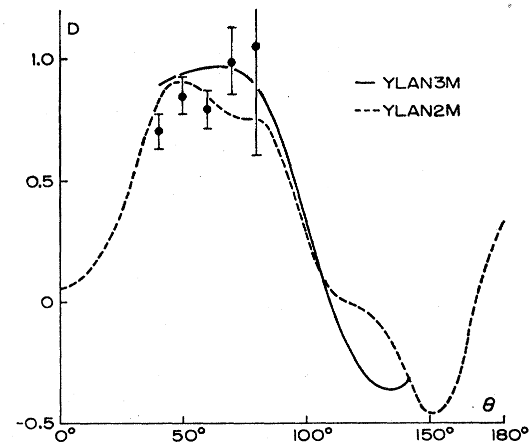

FIG. 3. Most probable experimental values of D, and theoretical predictions of phase parameter sets YLAN2M and YLAN3M of Breit and co-workers.

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