Scattering of 314-Mev Polarized Protons by Deuterium*

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(Received April 9, 1954)

The polarization of deuterium for 314-Mev protons has been examined as a function of angle. A beam of 314-Mev protons about 60 percent polarized was scattered by a liquid deuterium target. Measurements were made of the asymmetry of scattering of fast protons, namely both elastically and inelastically scattered, as a function of angle. The polarization of protons by deuterons, inferred from the asymmetry, was found to be small at small angles, to be about 0.35 from 10° to 30° laboratory angle, to be zero at 45° and negative thereafter. The polarization of quasi-free proton-proton scattering measured with the two scattered protons in coincidence, was found to be zero at 41° and 49° laboratory angle within statistical error. The polarization of quasi-free proton-neutron scattering was computed from measurements with the scattered proton and neutron in coincidence and was found to be 0.56±0.12 at 29° laboratory angle. The polarization of elastic scattered protons was computed from measurements using absorbers chosen to discriminate between elastic and inelastic protons, giving 0.59±0.07 at 24°, 0.29±0.05 at 28°, 0.39±0.18 at 32°, and −0.05±0.16 at 35°±4° laboratory angle.

The polarization of protons by deuterium appears to vary with angle in approximately the same way as the proton polarization of H. One can say tentatively that the polarization of protons by neutrons at this energy has the same sign and about the same magnitude. The differential cross section of deuterium for scattering of protons is given as a function of barycentric angle of the $p-d$ system from 10 to 80 degrees.

INTRODUCTION

RECENTLY several investigations[1] have been made on polarization of protons scattered by hydrogen, showing large effects. The angular distribution of the polarization at 140 Mev indicates the dominance of the ^3P angular momentum state, and above 300 Mev there is evidence for the additional influence of the ^3F state. Evidence from scattering of protons on beryllium indicates a strong polarization of the elastically scattered protons, apparently stronger than the polarization due either to free $p-p$ scattering or to quasi-free proton-nucleon scattering at 310 Mev. Deuterium is interesting because the rather loose binding of the neutron permits the approximation of free $p-n$ scattering, and because the elastic scattering from the deuteron provides a transition from free nucleon-nucleon scattering to elastic scattering of beryllium. By examining the asymmetry of elastic scattering of polarized protons from deuterium one might hope to reach some understanding of polarization by elastic scattering from heavier nuclei.

Several different processes may occur when 300-Mev protons scatter from deuterium. The elastic scattering ($p+d\rightarrow p+d$) dominates at small scattering angles, and decreases rather slowly with angle. In addition there are events in which the proton transfers more energy to one or both nucleons. By quasi-free nucleon scattering we mean an event in which the proton and recoil nucleon emerge with approximately the angle and energy corresponding to a free proton-nucleon scattering. By asymmetry we mean that different numbers of protons are scattered at $+\theta$ and $-\theta$ measured from the beam direction.

In this work the asymmetry of the total scattered protons was measured as a function of angle. In addition, we attempted to separate and measure the elastically scattered protons at angles where it was feasible. Finally, at certain angles we have attempted to measure the quasi-free nucleon scattering, by requiring that the two nucleons mainly involved in the collision emerge coincidentally approximately 90° apart in the barycentric system of the two nucleons.

An unpolarized beam, such as the circulating proton beam of the cyclotron, is one for which the expectation value of the projection of the spin along any direction is zero. Such a beam may become polarized by a scattering, if the scattering is spin-dependent. When a previously unpolarized beam undergoes a spin-dependent scattering, there is no resulting asymmetry in numbers of scattered protons, but there is an asymmetry of scattered protons of given spin direction; that is, for a given direction the scattered protons have a net polarization. The polarization at a given angle P is defined as the difference between the fraction of the protons scattered with spin up and the fraction with spin down. In general, if a polarized beam undergoes a spin-dependent scattering, the probabilities for protons to be scattered on opposite sides of the beam will be different. For a scattering in the horizontal plane, the asymmetry A is defined as twice the difference between the numbers scattered to the right and to the left, divided by their sum. It is well known that the asymmetry resulting after the second scattering is maximal in the plane defined by the first scattering. There is no resultant asymmetry in a plane normal to the plane of first scattering, and this fact is used to test that the

* Research supported by a joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] Oxley, Cartwright, and Rouvina, Phys. Rev. **93**, 806 (1954); Chamberlain, Segré, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954); J. M. Dixon and D. C. Salter, Proceedings of the Fourth Annual Rochester Conference, 1954 (University of Rochester Press, Rochester, to be published); Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954).

detecting apparatus is properly aligned. If the first and second scatterings are equivalent, the second scattering may be used to evaluate the polarization due to the first scattering of a previously unpolarized beam. The relationship is $P=(\frac{1}{2}\text{ asym.})^{\frac{1}{2}}$. Where a first scattering produces the polarization P_1, and a second scattering would produce P_2 in an unpolarized beam, the effect of the two in succession is to produce an asymmetry given by

$$A=2P_1P_2.$$

EXPERIMENTAL ARRANGEMENT

In the experiment presented here the plane of the first scattering was the plane of the circulating cyclotron beam. The first scattering was chosen so that its angle and energy loss corresponded to an elastic scattering. Recent experiments of Strauch[2] indicate, however, that many inelastic processes in which the nucleus acts collectively and is left in any one of several excited states contribute to the scattering of protons in this energy range. We shall continue to call protons scattered with very small energy loss "elastically" scattered, nevertheless.

Only protons scattered to the right at a well-defined angle and energy could reach the experimental area through the collimation system. To measure the degree of polarization of this beam we scattered it a second time in a manner like that of the first scattering except that the energy at the second scattering is inevitably somewhat smaller. After the first scattering, quasi-free nucleon scattering was excluded from the external beam by magnetic selection in the field of the cyclotron. After the second scattering it was excluded from the measuring telescope by copper so thick that only elastically scattered protons could reach the telescope.

The angles of first and second scattering were chosen equal. The degree of polarization of the beam was then estimated from the measured asymmetry after double scattering from beryllium.

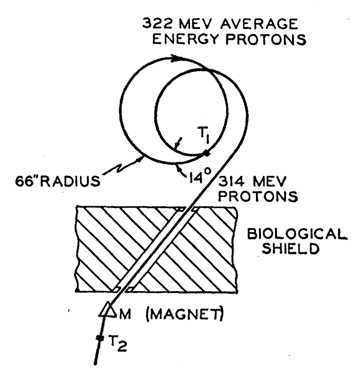

FIG. 1. Plan view of 450-Mev synchrocyclotron area, showing the experimental arrangement used to produce a 314-Mev proton beam, about 60 percent polarized in the vertical direction.

As shown schematically in Fig. 1, an internal beryllium target T_1 was placed at 66-inches radius (corresponding to 322-Mev average energy proton) in the 450-Mev Chicago synchrocyclotron. A beam of protons of energy 314 Mev, scattered at 14° from the beryllium target T_1, was analyzed in the fringing field of the cyclotron and emerged through the shield into the experimental area. It was collimated by a 1-inch vertical slit as it entered the shield and by a $\frac{5}{8}$-inch diameter collimator as it emerged.

The collimated beam was further analyzed with a magnet M in the experimental area, which deflected it about 20 degrees. The position of the deflected beam was found by vertical and horizontal exploration with a scintillation counter telescope at a position not far from the magnet. Then the beam was located at a second position by exploring with a second counter about 12 feet past the counter at the first position but connected in coincidence with it.

Next, a cathetometer was placed to look along the line of the beam defined by those two points. After this the cathetometer was used to align the second scatterer and in particular to see that the framework which held and swung the detecting counters symmetrically about the beam was coaxial with the beam.

This frame work was rigidly constructed of a 6-ft length of $3\frac{1}{2}$-in. pipe, turned smooth at two places, and mounted in V blocks on separate, adjustable tables, so that it could be accurately and conveniently placed to be coaxial with the beam. The counters were mounted on side arms fastened to the pipe, and counterweights were so placed that it was possible to rotate the counters to any position around the beam as an axis without the application of appreciable torque. The counters were rigidly clamped and the framework was stiff enough that the scattering angle to the counters θ_2 was accurately independent of rotary position of the framework.

After the magnet, the beam was defined by a 1-in. diameter round scintillation counter A. Next, a similar counter B was placed in the beam and was connected

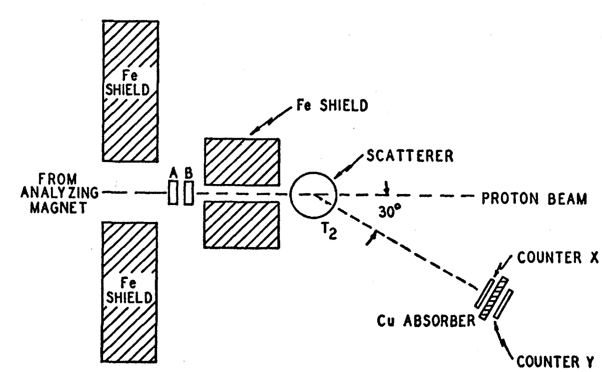

FIG. 2. Geometry for the second scattering.

[2] K. Strauch, Proceedings of the Fourth Annual Rochester Conference, 1954 (University of Rochester Press, Rochester, to be published).

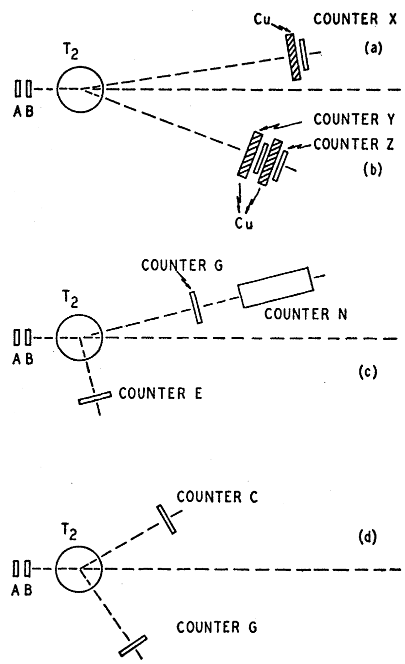

FIG. 3. Various arrangements of counter telescopes to detect scattered particles.

in coincidence with A to measure the incident proton flux, as is shown in Fig. 2. After passing through A and B the beam hit the second scatterer T_2.

The second scatterer was a liquid deuterium target. Deuterium gas was condensed in a metal Dewar using liquid hydrogen as refrigerant. By means of electrical heaters, the liquid deuterium could be switched from one container to the other, so that differences of the scattering with and without deuterium might be taken. Two cylindrical containers for the liquid deuterium were provided, one at the height of the proton beam and one above it. The container at the height of the beam was 4.23-inches inside diameter and 5 inches high. The temperature of the container was 24°K. The difference in the number of atoms of normal deuterium/cm² when liquid or gas fills the container is computed from the data of Woolley *et al.*[3] to be 4.96 $\times 10^{23}$ (1 ± 0.015). Of these, 98 percent are deuterium atoms and 2 percent hydrogen. The beam on entering or leaving the target had to pass through several layers of metal of total thickness 0.22 g/cm² of Al plus 0.12 g/cm² of brass.

The scintillation counters used to detect scattered particles were several in number, rather different from each other, and used in various combinations of coincidence and anticoincidence (see Fig. 3). For convenience in this discussion they are identified by letter and listed with appropriate descriptions of their characteristics in Table I.

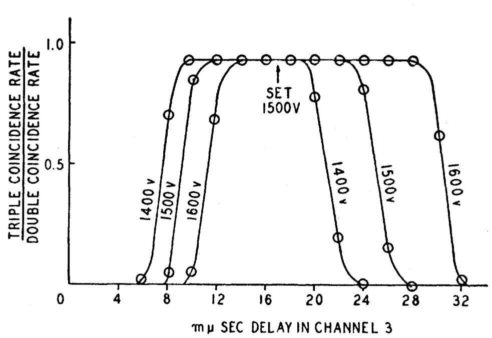

FIG. 4. Coincidence delay curves. Photomultiplier plateaus *vs* relative delay.

ELECTRONICS

The counters were connected in triple, quadruple, or quintuple coincidence and anticoincidence combination. To adjust the electronics for any such combination the following procedure was followed. The counters to be used were placed in the 314-Mev proton beam. A and B were connected in double coincidence. The delay of counter A with respect to B was varied, and coincidences per second plotted as a function of angle. This was done (e.g., see Fig. 4) for a range of voltages on the photomultipliers of A and B and for various attenuations of the coincidence pulse as it entered the recording scaler. When it was evident that the system was operating on a plateau both with respect to pulse attenuation and photomultiplier voltage, the delay of A was set to the value at the center of such a delay curve as in Fig. 4. Now a third counter (e.g., X) was connected in triple coincidence with A and B. The triple coincidence rate per unit double coincidence (ABX/AB) was plotted *vs* delay of counter X, for various values of the voltage on the photomultiplier of X, and for various attenuations of the pulse ABX as it entered the scaler which recorded it; from these data a proper choice of the delay for X was made.

TABLE I. Characteristics of the detecting counters.

Scintillation counters	Diameter, in.	Description
A and B	1	plastic, $\frac{1}{8}$ in. thick
C and D	$5\frac{1}{4}$	liquid, $\frac{1}{2}$ in. thick
E	$4\frac{1}{2}$	plastic, $\frac{1}{4}$ in. thick
G and H	6	plastic, $\frac{3}{8}$ in. thick
N	$5\frac{1}{2}$	liquid, 14 in. long (for detecting neutrons)

In a similar manner a fourth counter was added in quadruple coincidence if the measurement so required, and in the case of the $p-n$ coincidence measurement, a fifth counter was similarly added in anticoincidence. This procedure insured that the electronics were ad-

[3] Woolley, Scott, and Brickwedde, J. Research Natl. Bur. Standards **41**, 379 (1948).

justed to give flat-topped counting rate curves when the delay in any channel was varied.

The 314-Mev beam intensity was ~1000 protons/inch² sec. The counting rate loss was less than 1 percent, even for the double coincidence rate of counters A and B. The counting rates of the telescopes ranged from a few hundred counts per minute to a few counts per minute.

ESTIMATION OF DEGREE OF POLARIZATION OF BEAM

The magnetic field at the position at 66-in. radius in the cyclotron and the energy spread of protons in the equilibrium orbit at this radius[4] define the energy of protons striking the target to be 322±10 Mev. From the parameter of the proton channel as defined by the two collimating slits and from the radial dependence

TABLE II. Asymmetry of total protons scattered by D *vs* angle. Counter geometry as shown in Fig. 3a.

Counter	Distance from scatterer, inches	Laboratory angle degrees	Total Cu absorber between counter and scatterer, inches	Asymmetry %
E	$44\frac{1}{4}$	8±3	$2\frac{3}{4}$	15 ±13
C	$30\frac{3}{4}$	11±5	2	45 ± 4
C	$46\frac{1}{4}$	16±3.5	$2\frac{1}{2}$	51 ± 7
D	46	20±3	$1\frac{5}{8}$	43.5± 6.5
D	46	26±3	$1\frac{1}{2}$	31 ± 6
G	31	28±4.5	$1\frac{1}{4}$	20.5± 4.5
E	$47\frac{1}{2}$	29±3	$1\frac{3}{16}$	42 ± 8
G	28	32±6	$1\frac{1}{4}$	17 ± 4
E	$47\frac{3}{8}$	35±3	1	34 ± 9
[a] { G	26	42±6.5	0 }	6 ± 7
{ H	27	42±6.5	$\frac{7}{8}$ }	
E	40	44±4	$\frac{11}{16}$	−22 ±12
[a] { C	$25\frac{1}{4}$	49±6	0 }	−9 ± 6
{ D	26	49±6	$\frac{1}{2}$ }	

[a] Geometry as shown in Fig. 3b. In these cases quadruple coincidence rate was recorded, i.e., $ABGH/AB$ and $ABCD/AB$.

of the magnetic field of the cyclotron we estimate the internal scattering angle as 14° (right). Range measurement of protons in the external beam and width of the beam after magnetic deflection define the energy of the beam as 314±11 Mev in one case and 310±11 Mev in the second case. The second scatterer was a piece of beryllium 2 in. thick. The asymmetry was measured as in Fig. 3a with counter X set at 14°, covered with various thicknesses of copper, and connected in coincidence with A and B. As the thickness of copper increased, the triple coincidence counting rate became vanishingly small, and the asymmetry increased rapidly; see Fig. 5.

We take 70-percent asymmetry as the limiting asymmetry for elastically scattered protons at 14°. $P_1=(\frac{1}{2}\times 0.7)^{\frac{1}{2}}=60$ percent is the figure we shall assume here for the polarization of beryllium at 14°. To this quick estimate many objections can be brought,

[4] A. H. Rosenfeld (private communication).

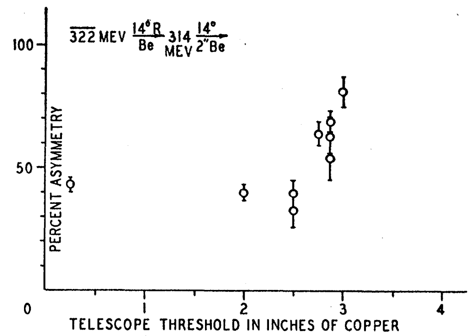

FIG. 5. Asymmetry *vs* energy threshold of the detecting counters. First scattering, 322-Mev p on Be, at 14° to the right. Second scattering, 314-Mev p on Be, at 14°.

chief of which is that the protons accepted after the second scattering through 3 inches of copper may not be scattered in a process similar to the first scattering.[2] However, the dependence of the polarization on (asymmetry)$^{\frac{1}{2}}$ makes P relatively insensitive to error in the asymmetry.

MEASUREMENT OF ALL SCATTERED PROTONS

The asymmetry of all scattered fast protons was measured as a function of angle from 8° to 48° laboratory angle. The detecting apparatus was sometimes a single counter, covered with enough copper to stop deuterons as in Fig. 3a and connected in a triple coincidence with counters A and B. Sometimes it was a telescope composed of 2 counters (see Fig. 2) connected in quadruple coincidence with counters A and B, the copper absorber for excluding deuterons being sandwiched between the two counters of the telescope. The latter arrangement was especially useful in that the quadruple coincidence reduced the large background of chance coincidences which existed at small angles in the triple coincidence arrangement. A typical measurement is discussed here briefly. Counter G was set at 31.7° laboratory angle, at a distance of 28 in. from the scattering center. It was covered with $1\frac{1}{4}$-in. copper to exclude deuterons. It was connected in coincidence with

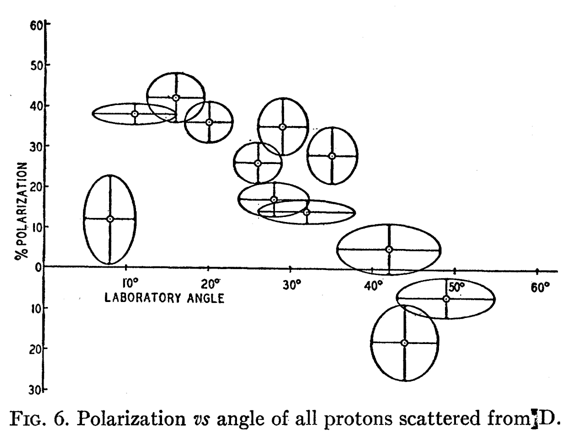

FIG. 6. Polarization *vs* angle of all protons scattered from D.

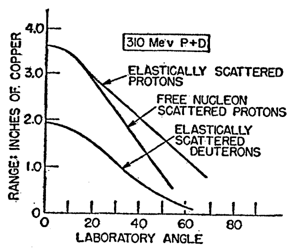

FIG. 7. Range in copper of the scattered particles. Upper curve: protons from elastic $p-d$ collisions. Center curve: protons scattered by a free nucleon. Lower curve: deuterons from $p-d$ scattering.

counters A and B; the counting rates ABG and AB were measured. With counter G to the left, and with deuterium in the scattering chamber, there were 2636 triples (T) for 80×10^5 doubles (D). Without deuterium, $T/D=250/32\times10^5$. With counter G to the right, and with deuterium, $T/D=3421/91\times10^5$; without deuterium, $T/D=225/30\times10^5$. The asymmetry, defined as $2(R-L)/(R+L)$, is calculated from these data to be 0.14 ± 0.03.

In Table II are listed the various measurements made on asymmetry of all scattered protons. The value of polarization calculated from these asymmetries are plotted in Fig. 6.

MEASUREMENT OF ELASTIC-SCATTERED PROTONS

One expects to be able to examine the reaction $p+d\rightarrow p+d$ separately from the reaction $p+d\rightarrow p+p+n$ by catching the deuteron and proton in coincidence in two counters properly placed. However, at all proton angles much different from 45° the deuteron recoils at almost the same angle as a proton scattered from a quasi-free $p-p$ collision in the deuteron; consequently such a separation must be made either by pulse height differentiation, which we were not prepared to do, or by range differentiation.

It is apparent from the curves of Fig. 7 that below 20° absorbers do not distinguish between protons from elastic and inelastic scattering. At larger angles it becomes possible to attempt separation with absorbers. As used here, this is not a clean method. In any case the momentum distribution of nucleons in the deuteron smears the curve for nucleon-scattered protons into a broad energy band. In these experiments the low proton flux in the external proton beam required the use of counters of poor angular resolution. So for a given solid angle and for a given absorber thickness, some nucleon-scattered protons were able to penetrate on the small-angle side of the counter, and some elastically scattered protons were cut off on the large-angle side of the counter, owing to the steepness of the curves in Fig. 7.

In Table III are listed the measurements made on mainly elastic-scattered protons. Asymmetries have been reduced to polarizations and are plotted in Fig. 8

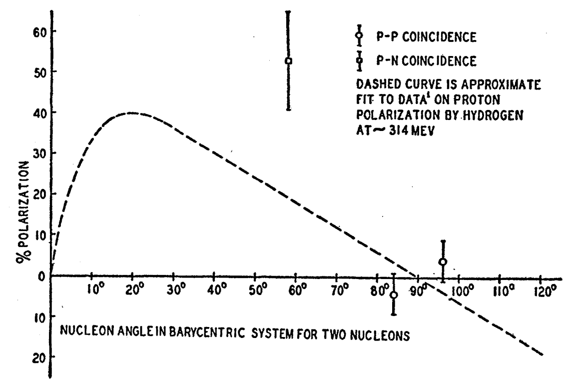

FIG. 9. Polarization of a nucleon scattered by a quasi-free nucleon-nucleon collision *vs* angle in the barycentric system of two nucleons. The $p-n$ polarization value is plotted at the angle of the scattered neutron.

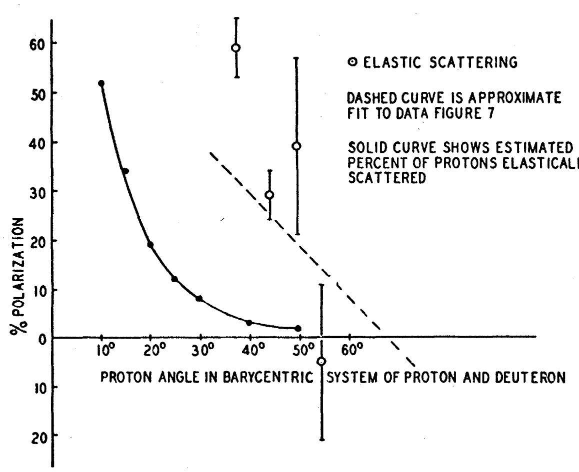

FIG. 8. P, Polarization *vs* angle in the $p-D$ center-of-mass system for protons scattered by deuterium. For these measurements the detecting counters had copper absorbers in front which excluded nearly all particles except protons elastically scattered from deuterium. However, at angles less than 30° the discrimination is incomplete.

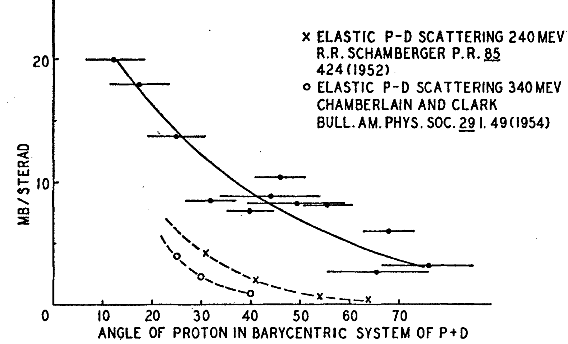

FIG. 10. Differential cross section for 310-Mev protons on deuterium to produce fast protons.

against the proton angle for the barycentric system of the proton and deuteron. It seems that the polarization by elastic scattering is as large as the total polarization, and perhaps slightly larger.

MEASUREMENT OF QUASI-NUCLEON-SCATTERED PROTONS

As we have said, the deuteron recoils very closely at the same angle as a proton scattered in a quasi-$p-p$ collision except in the neighborhood of 45°. Therefore we have made only one coincidence measurement of the two protons from a quasi-$p-p$ collision, this being the counter G at 42° laboratory angle, 26 in. from the scattering center, and with counter C on the other side of the beam at 48° and $25\frac{1}{4}$ in. Neither counter alone defined the solid angle. Quadruple coincidences rate $ABCG$ and double coincidences rate AB were measured simultaneously. The result was an asymmetry of -5 ± 7 percent for 42° and consequently $+5\pm7$ percent for 48°. That is, the asymmetry is essentially zero in this region. These values have been converted to polarization and plotted in Fig. 9, where also is shown the polarization by free $p-p$ collisions[1] at the same energy.

One measurement only was made of asymmetry due to quasi-free $p-n$ collision. For this, the neutron counter N was put at 29° with its front face 21 in. from the scattering center. Counter G was placed in anticoincidence in front of counter N, at the same angle and 14 in. from the scattering center. On the other side of the beam was counter E at 61°. A quintuple combination was measured: $ABEN$ in coincidence, with G in anticoincidence. The quintuple coincidence rate and the double coincidence rate were measured simultaneously, and gave an asymmetry of 68 ± 14 percent for 29°. This also has been reduced to quasi-$p-n$ polarization and is plotted in Fig. 9 at the angle of the scattered neutron where it is seen to be larger somewhat beyond statistical error than the free $p-p$ polarization at the same energy.

TABLE III. Asymmetries of mostly-elastic-scattered protons.

Laboratory angle, degrees	Counter	Distance from scatterer to counter, inches	Absorber between counter and scatterer, inches Cu	Telescope geometry shown in	Effective thickness of copper, inches	Asymmetry %
$24\pm5.5°$	C D	27 30	0 $2\frac{5}{8}$	Fig. 3b	$2\frac{5}{8}$	71 ± 8
$28\pm5.5°$	G H	31 32	$1\frac{1}{4}$ $2\frac{1}{4}$	Fig. 2	$2\frac{1}{4}$	35 ± 6
$32\pm6°$	G E	28 29	$1\frac{1}{4}$ $2\frac{1}{4}$	Fig. 2	$2\frac{1}{4}$	47 ± 22
$35\pm4°$	D	40	2	Fig. 3a	2	-6 ± 19

TABLE IV. Differential cross section for scattering of protons by deuterium.

Laboratory angle of proton degrees	Barycentric angle of scattered proton degrees	Differential cross section in barycentric system mb/sterad	Differential cross section in laboratory system mb/sterad
7.9 ± 3.7	13 ± 6	19.9 ± 0.3	50.7 ± 0.7
11.2 ± 5	18 ± 8	18.0 ± 0.7	45.2 ± 1.9
16.1 ± 3.5	25 ± 6	13.8 ± 0.2	34.7 ± 0.5
20.4 ± 3	32 ± 5	8.5 ± 0.5	20.7 ± 1.3
25.6 ± 3	40 ± 5	6.7 ± 0.4	15.8 ± 1.0
28.4 ± 6	44 ± 10	8.9 ± 0.4	20.0 ± 0.9
29.4 ± 3	46 ± 5	10.4 ± 0.9	23.3 ± 2.0
31.7 ± 6	50 ± 10	8.4 ± 0.3	18.4 ± 0.7
35.5 ± 3	55 ± 5	8.4 ± 0.8	17.8 ± 1.6
42 ± 7	66 ± 11	2.8 ± 0.2	4.8 ± 0.3
43.6 ± 3	68 ± 5	6.1 ± 0.7	11.6 ± 1.4
49 ± 6	77 ± 10	3.4 ± 0.1	6.1 ± 0.3

DIFFERENTIAL CROSS SECTION FOR SCATTERING OF PROTONS BY DEUTERIUM

In all these measurements of asymmetries the incident 314-Mev proton flux is measured directly with counters A and B in coincidence. So in principle an absolute cross section for scattering by deuterium of all protons fast enough to penetrate the copper barrier against deuterons (i.e., at small angles of energy above 200 Mev and decreasing to 80 Mev at 50° lab, see Fig. 7) can be calculated. For this purpose, we estimate 4.86×10^{23} atoms D/cm^2. A correction has been made for the loss of protons in the copper absorbers, using the range curve in copper for 314-Mev protons, from which the energy of the protons was determined. These corrections range from 8 to 30 percent. But this procedure underestimates the corrections somewhat for the reason that the range curve was taken with a proton beam of about 1-in. diameter whereas the asymmetry measurements were made with protons incident over the entire face of the $5\frac{1}{4}$-in. diameter counter. Even though this experiment was not designed to measure cross sections, and the corresponding values are not of high quality, nevertheless, in Table IV we give the results for what they may be worth. The total differential cross section for scattering of fast protons in the barycentric system is plotted in Fig. 10 *vs* barycentric proton angle.

Although we do not plot it here, a best curve through the data seems easily consistent with an artificial variable composed of the sum of differential cross sections at 314 Mev for (a) $p-p$ scattering, (b) $p-n$ scattering, and (c) $p-d$ elastic scattering.