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Double Scattering of High Energy Protons * ‡

by

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ABSTRACT

Measurements of polarization effects in double scattering of protons have been made in the energy range near 200 Mev. With a first scattering angle of 19° and a mean second polar angle of 27° , the azimuthal asymmetry 2ϵ , the fractional difference between flux at azimuths 0 and 180° , has been determined with several first and second target materials. With polyethelene second target, an effective hydrogen target was realized by detecting in coincidence the scattered and recoil protons. By successive use of carbon and polyethelene first targets with an effective hydrogen second target, the asymmetry in double p-p scattering was determined by subtraction to be $9.6^{+3.5}\%$. Since the fractional polarization, P , in a single scatter is related to the asymmetry in a double scatter by $2\epsilon = 2 P^2$, the polarizations produced in single scatters from hydrogen and carbon were found to be, neglecting energy degradation and angle change, $P_H = 22^{+4}\%$ and $P_C = 43^{+8}\%$. A comparison of the p-p asymmetry with those calculated by Goldfarb and Feldman using current p-p force models shows that the repulsive core model of Jastrow which best predicts the observed single scattering differential cross sections yields far too little polarization. Considerable singular non-central force as used in

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other models seems indicated. The polarized protons produced in scattering from carbon may be useful for other experiments. The polarizations in scattering from several elements in the range from D to Cu, as measured with hydrogen analyzer, vary from 20 to 50%.

I. INTRODUCTION

In 1951 at the conclusion of proton-proton scattering experiments at 240 Mev¹ a considerable amount of information on high energy nucleon-nucleon scattering was available. The theoretical analyses gave no unique information regarding proton-proton forces, but several potential models had been constructed particularly to fit the proton scattering results from the 32 Mev² and early 350 Mev³ experiments. Christian and Noyes⁴, using singular tensor force terms, fitted those data, but did not preserve the charge independence of nuclear forces. In an effort to maintain charge independence, Case and Pais⁵ used singular triplet spin-orbit interactions of the L·S form. Jastrow⁶ resorted to the alteration of the singlet well by the introduction of a hard central core, and with some non-singular tensor interaction was also able to fit the data without sacrifice of charge independence.

Further proton-proton scattering data at small scattering angles which had become available⁷ did not fit the predictions, particularly of Case and Pais and of Christian and Noyes.

With this as the prevailing situation, we considered the feasibility of an investigation of non-central forces by measurement of polarization effects in a double scattering experiment. The interpretation of any measured effect probably would again require computations based on nuclear force models since no common nuclear parameter is directly measured. The only calculations available, those of Wolfenstein,⁸ were, unfortunately, based on nuclear models outmoded by high energy scattering data, and predicted very small polarization effects in double proton-proton scattering.

The experiment was nevertheless undertaken since it was possible that appreciable effects might be present as suggested by the use of sizeable non-central terms in the models constructed. The measurement of such effects might then allow some choice among proposed models.

II. ASYMMETRY RELATIONS IN DOUBLE SCATTERING.

Wolfenstein and Ashkin⁹ have given a general derivation of the relation between polarization produced in a single scatter and the asymmetry observed in a double scatter. For purpose of illustration we consider a particular case in which spin flip of the proton in scattering does not occur, as for example in proton-proton scattering.

Consider protons scattered at an angle θ in a plane $\phi = 0$. If there are non-central forces involved, the scattered beam will be, in general, partially polarized perpendicular to the plane of scatter. The polarization may be considered as due to a difference in scattering cross sections for the two spin orientations in the incident beam. Thus we may write:

$$\begin{aligned}\sigma_+(\theta) &= \sigma_0(\theta) \{1 + \delta(\theta)\} \\ \sigma_-(\theta) &= \sigma_0(\theta) \{1 - \delta(\theta)\}\end{aligned}\tag{1}$$

For an incident unpolarized beam, the fractional polarization $P(\theta)$ of the scattered beam is

$$P(\theta) = \frac{N_+ - N_-}{N_+ + N_-} = 2 \langle S_y \rangle = \delta(\theta)\tag{2}$$

If this scattered beam undergoes a second scattering, again limited to this plane, and in the same sense, i.e. at $\phi = 0$, relations similar to (1) will hold. Since target materials, angles and incident energies of scattering will, in general, be different, primed quantities are used for the second interaction. From the partially polarized beam we will obtain the following fluxes:

$$\begin{aligned}N_+ &\propto \sigma_0(\theta) \{1 + P(\theta)\} \sigma_0'(\theta') \{1 + P'(\theta')\} \\ N_- &\propto \sigma_0(\theta) \{1 - P(\theta)\} \sigma_0'(\theta') \{1 - P'(\theta')\}\end{aligned}\tag{3}$$

$$\text{Adding, the total flux is : } N' \propto \sigma_0(\theta) \sigma_0'(\theta') \{2 + 2 P(\theta) P'(\theta')\}\tag{4}$$

and in general it may be shown that

$$N^{\circ}(\phi) = N_0^{\circ}(1 + P P^{\circ} \cos \phi) = N_0^{\circ}(1 + \epsilon \cos \phi). \quad (5)$$

Experimentally this dependence of the flux on the angle ϕ is conveniently measured by the asymmetry,

$$2 \epsilon(\theta, \theta') = \frac{N^{\circ}(0^{\circ}) - N^{\circ}(180^{\circ})}{1/2 [N^{\circ}(0^{\circ}) + N^{\circ}(180^{\circ})]}. \quad (6)$$

The polarization-asymmetry relations have been proved for the case of two body collisions. For high energy disintegrating collisions, we will assume that they hold also in a statistical sense.

III. CONSIDERATIONS IN APPARATUS DESIGN.

In a double scattering experiment, intensity is clearly a major problem. We were therefore led to consider the use of a first target in the circulating cyclotron beam. Sufficient intensity of the first scattered beam is obtainable by locating the second scattering apparatus immediately outside the cyclotron vacuum tank. Since the primary interest was in the double scattering from hydrogen, and a liquid hydrogen target was impractical, it was planned to use a polyethylene, $(CH_2)_n$, first target and to select the proton-proton scatters by the coincidence between the scattered and recoil protons. In order to detect the recoil protons, it is necessary to place a counter below the circulating beam and to use protons scattered at a small upward angle from the median plane. This has the advantage that the scattered protons leaving the cyclotron depart from the median plane and enter a region of lower background. Under these conditions, however, the radial component of the magnetic field may cause depolarizing transitions. Adiabatic conditions do not prevail as the proton leaves the field. A semi-classical calculation yields a

transition probability of $< 2\%$, a negligible amount. Depolarization may also occur as the proton traverses the materials of the scattering equipment. The cross section for this process is given by Wolfenstein⁸ as $6 \times 10^{-30} (Z^2 + 2Z) \text{cm}^2$, producing negligible depolarization in the thickness of material likely to be involved.

Since the estimates of second scattered intensity were low, we were led to sacrifice angular resolution for intensity. Because of this and other practical considerations, a fixed polar angle experiment was planned. One consideration in choosing this angle was the expected variation of asymmetry with scattering angle. The only available calculations were those of Wolfenstein⁸ based on a model which is known to predict incorrectly the nucleon-nucleon single scattering. These calculations predict an asymmetry of less than 1% with a maximum near 35° c.m. for 100 Mev protons. An examination of the terms in the asymmetry expression leads one to expect the effects in general to persist over a fairly broad range of angles near 45° c.m. (For identical particles the polarization is zero at 90° c.m.)

Another consideration in the choice of scattering angle is the desirability of a small energy loss in the first scatter as afforded by a small scattering angle; to a first approximation the energy difference of protons incident on the first and second targets may then be neglected. It would also be preferable to have first and second scattering angles approximately equal for straightforward interpretation.

In the second scattering a polyethylene target with coincidence detection of the proton-proton scatters is again advantageous. The need for detection of both protons limits the second scattering angle to those large enough to give a recoil of at least 30 Mev.

The above requirements are compromised with a first scattering angle of 19° lab. and a median second scattering angle of 27° lab.

In order to measure the scattered flux as a function of the azimuthal angle ϕ , it is necessary to provide means to vary ϕ without changing the geometry or detection efficiency. This may be done by mounting the whole second scattering apparatus in cylindrical geometry and then rotating it as a unit. Provision must then be made to align the mechanical axis with the first scattered beam.

A modification of the above general plan was found necessary because the defocusing effects of the fringing field of the cyclotron reduced the efficiency of detecting the first p-p scatter in coincidence. It was found, however, that of the scattered protons from polyethelene, enough were from the hydrogen to make feasible a difference determination by comparison with carbon target scattering. Consequently the counter for detection of the first p-p recoil was discarded except for determining the p-p scattered proton trajectory.

IV. APPARATUS

The general arrangement of the apparatus is shown in figure 1. The first target intercepts the 220-230 Mev circulating beam of the synchrocyclotron. Protons scattered at about 19° are collimated and selected roughly in energy at the edge of the pole tip and leave the cyclotron vacuum chamber through a thin window. A broad channel in massive lead and copper shielding allows the protons to enter the second scattering apparatus, which is contained in a cylindrical shell. A magnetic shield reduces the cyclotron fringing field sufficiently to eliminate appreciable distortions of second scattering geometry.

The cylinder is a rigid mechanical structure, supported near each end in order that it may be rotated about its axis. The supports are adjustable so that the mechanical axis may be made to coincide with the beam.

Figure 2 shows the second scattering apparatus as mounted within the cylindrical shell. The useful beam is defined by an axial cylindrical stilbene

counter, 0.75 cm. in diameter. A .5 cm. diameter target of polyethylene, also on the axis, is interchangeable with one of carbon for background evaluation. The targets are suspended from a frame mounted on a carriage providing accurate motion of the targets perpendicular to the plane of the figure. Protons scattered in a range about 27° pass into a two counter telescope. A copper absorber placed between the counters of the telescope rejects protons of less than about 100 Mev. The recoil proton from the p-p interaction is detected by a single conjugate counter. As shown, copper blocks shield the telescope and recoil counters from protons scattered in the axial counter. The auxiliary exploratory counter of the same size as the axial counter was used in coincidence with it to ascertain the direction of the first scattered beam. The mechanical axis was then shifted to coincide with this direction.

In order to place the photomultiplier tubes in a region of low field, long light pipes mounted within the cylindrical shell were used. All photomultipliers were located within a large magnetic shield and in addition were individually shielded with mild steel and Mu metal.

Fourfold coincidences were formed among pulses from the axial counter, the two telescope counters, and the conjugate recoil counter. Figure 3 shows a block diagram of the electronic equipment. Pulses from each counter were amplified by a wide band chain amplifier (SKL Model 202) and fed into a coincidence circuit of a modified Garwin¹⁰ type with a resolving time of about 10^{-8} second.

Several types of beam monitor were used during the course of the experiment. One method was to count the useful proton beam as measured by single counts in the axial crystal. Only a negligible fraction of the singles in this counter were from other than beam protons; however, the counting rates, of the order of 10^6 per second instantaneously could not be counted with complete reliability by the scaling units available. Indirect methods measured

either the fast neutron flux from the target or the general slow neutron flux from the cyclotron. In any case the monitor used was compared at low beams with the axial crystal counting rate and shown to be proportional to the scattered proton beam flux.

V. EXPERIMENTAL PROCEDURE AND AUXILIARY CHECKS.

Alignment

In order to locate the second scattering apparatus, the trajectories of the p-p protons from a polyethelene first target were traced by using the counter for detection of the p-p recoil near the cyclotron lower pole face in coincidence with a search crystal outside the cyclotron tank. The collimator at the edge of the pole tip was adjusted in position to maximize this beam. The range of the scattered protons was found to agree with that expected from the scattering angle.

Before placing the second scattering apparatus in position the critical components were optically aligned on the mechanical axis. The axial crystal, which fitted snugly in a hole in a lucite light pipe, was removed to permit sighting along the axis. The polyethelene and carbon second targets were aligned in turn and motion stops set so the targets could be returned to axial position with the remotely driven carriage. The light pipe position is adjustable so that the axial counter could also be set on axis. The exploratory beam aligning counter is movable by a selsyn driven carriage along a line perpendicular to the cylinder axis. The index reading corresponding to axial position of this crystal is determined during the optical alignment. The alignment of these various elements were made to within $1/10$ the radius of the element aligned.

The second scattering apparatus is positioned approximately from the trajectory previously traced. The beam direction relative to the mechanical axis is then found by observing the coincidence rate between axial and exploratory counters as the auxiliary counter is moved. This is done at two

rotational positions of the second scattering apparatus, thus tracing across the beam a profile in perpendicular directions. The mechanical axis is then reset to coincide with the beam direction and this alignment is checked by repeating the procedure. The profiles indicate an approximately cylindrically symmetric beam with full width at half maximum of 1.8° see Figure 4. This enabled the mechanical axis to be set within 0.2° of the beam direction.

Background Evaluation

The fourfold coincidence rate included, in addition to the p-p events, a background which was evaluated by replacing the polyethelene second target by one of carbon. The diameter of the carbon target was such that the same amount of carbon was present in the carbon as in the equal length polyethelene target. Under this condition the energy loss of the scattered protons was approximately the same for the two targets.

The possible sources of background coincidences included actual coincidence scatters from carbon and various chance coincidence combinations which may or may not require the presence of the carbon target. By means of delaying the pulses from the several counters it was ascertained that the background was due to two principal sources. The first was an accidental coincidence between a recoil counter pulse and a true event in the other three; the second source was an accidental combination of pulses in the axial and recoil counters with a true double in the telescope. Because of the directivity of the fast neutrons from the cyclotron, the background would be expected to be a maximum with the apparatus orientation $\phi = 0$, when the telescope points in the cyclotron direction. This was found to be the case. In order to show that there were no unevaluated background effects from this asymmetric telescope counting rate, the experiment was performed at a counting rate with one of the telescope counters omitted. The background, evaluated as before, was then about the same for all azimuthal positions of the scattering chamber, and the asymmetry in the p-p events was found to be the same as determined with

both telescope counters in operation. Thus the background evaluated with the carbon second scatterer included all contributions except those due to the presence of the hydrogen in the target.

The p-p scatters contribute some singly detected protons whose conjugates are lost in this geometry. The number of these scatters is small compared to the fourfold rate, which itself is extremely small compared to the singles rate in any one counter thus giving negligible chance contributions from this source. Another type of background dependent on the presence of the hydrogen is a true p-p scatter involving a proton which does not pass through the front counter. Coincidence in time of such an event with a proton passing through the front crystal (and not making a p-p scatter) would be incorrectly recorded as a true event. The number of such events was evaluated by means of delaying the front pulse. These accidental quadruples were found to be small in number and nearly symmetric with ϕ ; thus the background was accurately measured by the use of the carbon second scatterer, including any true coincidences from the carbon itself.

Counting Rates

A suitable compromise between adequate counting rates and low background with slow dependence on beam level was obtained with fourfold rates of about 40 counts per minute of which 5 to 15% were background. At these rates and with the asymmetries encountered, 10-15 minute runs gave sufficient statistical accuracy to allow significant comparisons to be made among runs of the same and different rotational position. These run durations were short enough to permit interspersal and repetition of regular and background runs at the several ϕ positions, in order to minimize any gradual time dependent effects. In each of the two independent series of runs carried out, there were approximately ten runs at each rotational position. The variations of counting rates from run to run, for any given rotational position, were well accounted for by statistical variation of the coincidence counts.

Further Procedure

Since our primary interest was in the determination of the double p-p asymmetry, we made observations with polyethelene and carbon first targets to determine the effect by difference. (In both cases the effective second target was hydrogen.) Somewhat surprisingly, large asymmetries were found with the carbon first target as a polarizer. For either target similar counting rates and background were found so that the procedures differed little.

After a series of runs with a carbon target, the first target was changed to polyethelene. No shift of beam direction at the second scattering apparatus was produced in such a target change. As one would expect, the ratio of true quadruple coincidences to neutron monitor counts changed with the target material, while the ratio of coincidences to scattered beam monitor counts remained the same. In the cyclotron beams used, appreciable chemical decomposition of the polyethelene with loss of hydrogen took place, necessitating several replacements of the first target. The loss, determined by chemical analysis, amounted to as much as 20% of the original hydrogen content.

p-p Contribution from CH_2 First Target

In making the CH_2 -C subtraction it was necessary to ascertain the fraction of the proton flux reaching the second target due to proton-proton first scatters in the polyethelene target. This fraction was determined by measuring for CH_2 and carbon targets the ratio of the true quadruples to the Be^7 γ activity induced by the proton bombardment of the carbon. The comparison of the ratio obtained with carbon and CH_2 as first target is a direct measurement of the relative numbers of p-p and p-c protons in the scattered beam. The Be^7 half life of 54 days enables a ready determination of the proton flux integrated over the bombardment time of a target. In practice, the coincidence to monitor ratio averaged over the four ϕ positions and over the runs made with a given target was found and the total monitor count during a target bombardment

was compared to its activity. With this procedure, the p-p contribution to the proton flux averaged over the period of gradual hydrogen loss was evaluated.

Singles Rate Effects

The directional neutron beam led to high singles rates in the individual counters, of the order of 10^5 /second instantaneously; these varied somewhat with rotation of the apparatus. This led not only to background effects which were evaluated, but also could have produced losses or gains in the recorded p-p counting rates, as a result of pile-up or of blocking in the amplifiers or coincidence circuit. The circuits were chosen to avoid these contingencies. In addition, checks were made to determine any asymmetry due to the high singles rates. The first consisted of a measurement of the singles rates in each counter for each azimuthal position. No counter changed counting rate by more than 10%; the front counter showed no change, as would be expected from its axial position. The sum of the singles rates in one azimuthal position differed from the sum in any other position by less than 1%, and thus no serious singles rates effect was expected.

Furthermore, measurements at half the usual beam differed in per cent asymmetry by $-2.2^{+3.3}$ from the full beam value of 18.3 determined in that series of runs.

Because of the high singles rates care was taken to insure that the photomultiplier dynode voltage supplied by a resistor condensor network remained constant in spite of the charge drained during a beam pulse.

Beam Structure

Possible asymmetry in the scattered flux could arise from an unsymmetric angular divergence of the beam together with misalignment of the target, axial crystal or mechanical axis with the proton beam. A direct estimate of the mis-

alignment effect may be made from the estimated uncertainties in alignment, the geometry of the apparatus, and the beam profiles observed as previously described. Such a profile is shown in Figure 4. The calculated extreme asymmetry due to misalignment of the front crystal and target is 3%.

Due to the fringing field of the cyclotron, there is a correspondence between the energy of protons and their angle of arrival at the second scattering apparatus. This may combine with absorption effects in the second target to give an asymmetry in the observed scattered flux, since in the $\phi = 180^\circ$ position the lower energy incident protons are concentrated on the side of the target which requires traversal through the target in order for the low energy conjugate proton to reach the counter. For incident protons of about 150 Mev there will be some loss due to stopping for some angles of scatter. This effect has been estimated on the assumption of a strict correspondence between energy and angle. In that case, with the relation between angle and energy established by floating wire measurements in the field and either the observed angular spread or the observed energy spectrum derived from range measurements, a 1.8% asymmetry was calculated. This is an overestimate, since the finite first target dimensions introduce a spread in angle for a given energy.

Residual Effect of Magnetic Field on Detection Efficiency

It is important to determine the effect of the magnetic field on photomultiplier sensitivity and thus detection efficiency as the apparatus is rotated. We first measured the multiplier sensitivities at the four positions $\phi = 0^\circ, 90^\circ, 180^\circ$ and 270° by noise spectrum observations. The extreme variations in pulse height were found to be less than $1\frac{1}{2}\%$ for all counters but one, which showed a variation of $2\frac{1}{2}\%$. To convert these pulse height observations to a measurement of detection efficiency variation, we examined, during each series of runs, the fourfold coincidence rate as the pulses from each counter were, in turn, attenuated 30%. Because of the thick second

target, the large angular acceptance, and the dispositions of the counters, some deviation from a flat plateau was expected. The variations in counting rate with pulse height expressed in terms of the logarithmic derivative, $\frac{H}{C} \cdot \frac{dC}{dH}$, typically were found to be, for the four counters, 0.34, 0.33, 0.46, and 0.15. Multiplying, in each case, by the corresponding extreme variations in sensitivity due to the magnetic field, the extreme variations in coincidence rate due to the individual counters were thus found to be 0.44%, 0.05%, 1.1% and 0.03%. Combining the effects in the individual counters the net variation in coincidence rate with position, due to magnetic field, was calculated to be +0.7%, +0.4% and -1.2% for, respectively, 180°, 90° and 270° referred to the zero degree position. This variation in detection efficiency was substantially independent of the first target material.

VI. PRESENTATION OF DATA

The data is presented in terms of the fourfold to monitor ratios in Table I. The background evaluated with carbon second target has been subtracted but is indicated in the table. The quadruple to monitor ratio averaged over all four ϕ positions was set equal to 100 so that the per cent asymmetries are directly indicated.

The scattered proton flux at each ϕ position is expected to vary as $1 + \epsilon \cos \phi$. The fluxes at the 90° and 270° positions are seen to be close to the average value over all ϕ .

From the data of Table I, the asymmetry 2ϵ defined in equation (6) is computed and presented in Table II. For polyethelene first target the fraction of proton flux reaching the second target due to proton-proton first scatters, f , in the polyethelene target was determined, in the manner previously described, and is presented for the two series of runs.

The asymmetry to be expected in an experiment using pure hydrogen as both first and second targets is determined from

$$(f-1) (2 \epsilon_{CH}) + f(2 \epsilon_{HH}) = 2 \epsilon_{CH_2, H} \quad (10)$$

where $2 \epsilon_{CH}$ is the asymmetry measured in the carbon first, hydrogen second experiment, $2 \epsilon_{CH_2, H}$ is the asymmetry measured in the CH_2 first, hydrogen second experiment, and $2 \epsilon_{HH}$ is the asymmetry to be expected in a pure hydrogen first, hydrogen second experiment. The derived values of ϵ_{HH} are also presented in Table II.

The first scattering was limited in θ to a range of 4 degrees centered about 20° and the collimator limited the energy of the proton flux impinging on the second target to the range 160-220 Mev. The protons of the 220-230 Mev internal cyclotron beam scattered from hydrogen and passing through the collimator are at $\theta = 18.5^\circ - 19.5^\circ$ and have energies 195-205 Mev. In scattering from carbon, because of this energy selection, we have essentially required a nucleon-nucleon collision within the carbon nucleus. (The angle of scatter is sufficiently large that only a small fraction of the scattered protons are those diffracted from the carbon nucleus.^{11,12}) Provided the protons incident on the second scattering apparatus exceeded 130 Mev the second p-p scattered protons penetrated the telescope and were detected in coincidence in the angular range $23^\circ - 31^\circ$. The width in angle ϕ accepted was 44° .

From equation 5, $\epsilon_{HH} = P_H(\theta, E) P_H^*(\theta', E)$. Assuming a slow variation of P_H with θ and E , which decreased from 225 to 200 Mev, we can take $P_H(\theta, E) = P_H(\theta', E')$ and find, for an intermediate energy the values of P_H given in Table III. Under the same assumption we find from $\epsilon_{CH} = P_C P_H$ the values of P_C also given in Table III.

VII. DOUBLE SCATTERING FROM CARBON

The practical difficulties involved in directly measuring double p-p scattering made a subtraction technique necessary. However, because of the large polarization of protons scattered from carbon, another method is available, in principle, for determining the polarization in proton-proton scattering. If the asymmetry, 2ϵ , in a double scattering from carbon targets is measured, the polarization produced in a single scattering from

carbon, P_C ($\sqrt{E} = P_C$, neglecting energy degradation) is obtained directly. Since the product, $P_C P_H$, has been measured from the asymmetry determination in the carbon first, hydrogen second, scattering experiment, this separate determination of P_C thus gives a value for P_H without recourse to a subtraction experiment.

The apparatus thus far described was changed in order to measure double scattering from carbon targets by omitting the pulse from the recoil counter and recording triple coincidences among the axial and telescope counters. The copper absorber between the telescope counters limited detection to high energy scattered protons. With a reduced beam it was possible to measure these triple coincidences at a rate of 15 per minute with a background of about 25%, as evaluated by removing the second target. As in the case of the fourfold arrangement, the rate of change of coincidences with pulse height attenuation in individual channels was slow. The procedure followed in collecting data was similar to that used previously.

The value of P_C determined by this statistically more accurate method did not disagree with the less accurate subtraction value. However, two successive runs using this "triples" coincidence scheme were in significant disagreement among themselves. The source of this defect has not been determined because of limited time available.

For the first set of runs the asymmetry was $49.5^{+8}\%$. For the second set of runs the double scattering from carbon yielded $2 \in = 25.5^{+4}\%$. The polarizations from the two determinations are $P_C = 49.8^{+4}\%$ and $P_C = 26^{+3}\%$ respectively, neglecting energy and angle change. The difference which demonstrated reproducibility gives a polarization of $43^{+8}\%$. Because of the unexplained discrepancy between the two "triples" determinations, these values are not combined with the asymmetry measured with carbon first and hydrogen second targets to give a value for the polarization from hydrogen.

VIII. ACCURACY AND CONSISTENCY OF MEASUREMENTS.

The accuracy of the measured asymmetries is limited largely by counting statistics. Several factors which may contribute systematic asymmetries have been examined and discussed in section V. The principal effects are due to the following: a) a combination of small target and axial counter misalignments with departure of the beam structure from cylindrical symmetry, b) changes in polar scattering angle with ϕ due to misalignment, c) absorption in the target with correlation of energy and angle of arrival, d) circuit loss or pile up with the change of singles counting rates upon rotation. These effects have been estimated using the results of auxiliary measurements. In several cases more direct checks were made, but with accuracy limited by counting statistics. The quoted uncertainties in asymmetries and polarizations in tables and text are statistical errors only. Errors from these other sources total about 3%.

Several checks which are obvious and desirable have not proved practical. An attempt was made to use the first scattered beam from an internal target placed to give the mirror angle of scattering, so that the asymmetry would be reversed. This required a traversal of the scattered beam through about 180° in the cyclotron field. The attempt was abandoned when it was found that the intensity was low and that this beam could not be safely assumed to have a small contribution from protons which had struck the cyclotron dee. A change in angle of scatter would have been desirable, but the limitations imposed by the need for a high energy beam for the second scattering, and the need to bring the scattered beam out of the tank limited the angular range severely.

The proper variation of the second scattered flux with azimuthal angle, together with the repeatability of the measurements provide internal checks on the experiment.

Furthermore, several preliminary experiments made with different coincidence

circuits, target holders, magnetic shielding, second scattering chamber positions and radiation shielding, and made at various background levels, although of considerably less accuracy than the present experiment, gave results in general agreement with those reported here.

IX. DISCUSSION

During the course of the experiment, Goldfarb and Feldman¹³ and Swanson¹⁴, have made polarization calculations based on specific models of the proton-proton interaction. At 240 Mev the approximate predictions for 2° considering the angular acceptance of the apparatus is 0.5% ¹³ for the Jastrow hard core model, 13% ¹³ for the Christian-Noyes tensor model, 30% ¹³ for the Case-Pais L'S coupling model, and 8% for Swanson's¹⁴ revised Christian-Noyes model. Characteristic of the Christian-Noyes and Case-Pais models which predict the large polarization effects, as indicated by our results, is the use of singular non-central forces. Comparison of these predictions with the experimental results must be made with caution. The models give fits with the observed single scattering which vary from fair to poor; relativistic effects, which have been omitted, may influence the polarization; and the cut offs used with the singular potentials are to some degree arbitrary.

The calculations of Goldfarb and Feldman made by more exact methods than the Born approximations used by the originators of the several potential models give considerably modified predictions for single proton-proton scattering. Using the results of these calculations Noyes and Camnitz¹⁵ have considered the modification of the scattering at small angles by the Coulomb force. If we now compare the predictions based on the several models with the high energy proton-proton scattering results now available,⁷ we find that only the Jastrow model gives the proper flat p-p cross section extending to small scattering angles. The Christian-Noyes and Swanson models give results too large there largely as a result of the singlet scattering from a square or Yukawa well. Single p-p scattering seems therefore to require modification of the singlet

potential. The severe modification in the Jastrow model with its accompanying use of smaller, non-singular, non-central contributions is, however, inconsistent with our results.

Further information is available in principle from a measurement of the proton-proton polarization as a function of energy and especially as a function of angle of scatter. Such data, in addition to the magnitude of the effect, might yield further indication for a selection between tensor and L'S non-central forces. The higher angular momentum terms in the polarization which are favored by an L'S interaction would shift the angle of maximum polarization from the angle predicted by tensor forces, as is indicated, for example, by the calculation of Goldfarb and Feldman. Such experiments would be more practical at somewhat higher energies than we have used, since thick target absorption effects would be less limiting.

The sign of the p-p polarization is undetermined in our experiment, except that it is the same as that in the scattering from carbon. The sign relative to that in the neutron-proton case should be available through experiments with deuterium.

X. POLARIZATION BY D, Be, B, Li, C, Al, Si, Cu, AND Ag.

The observation of the polarization of high energy protons in scattering from carbon has led us to make an exploratory investigation of the polarization in scattering from several elements. Possible mechanisms will be discussed at the end of the section. It is apparent, however, that the high polarization in scattering from carbon may result from characteristics of nuclear forces in aggregates, and therefore data regarding the polarization may provide interesting information about nuclear forces if suitable theoretical analyses prove possible.

The present studies have resulted in the measurement of polarization by nine elements in the range from deuterium to silver. We have made these

measurements at a fixed polar angle of about 20° and with hydrogen as the analyzer (second scatterer).

Method

The method used to investigate the polarization of high energy protons in collisions with various elements was the same as that employed in the determination of the polarization of protons in collisions with CH_2 and carbon. The fractional polarization of a high energy proton beam scattered at about 20° from the particular element investigated was measured by the asymmetry in the flux of protons scattered from an effective hydrogen target placed in the polarized beam.

The nature of the proton-nucleus collisions which give rise to these high energy scattered protons is discussed later. The energy and angular range of first scatter are such that the process of scattering is the same for all elements; in particular, diffraction scattering contributes a small component to the proton beam, compared with quasi-nucleon-nucleon scattering.

The absorber in the high energy telescope of the second scattering apparatus put a lower limit on the energy of first scattered protons that could give rise to a detectable event in the second scattering apparatus. This was 130 Mev, below which energy there were essentially no beam protons. The polarization produced in the first scattering from the element bombarded is immediately derivable from the asymmetry measured in a double scattering, by use of the relation given in equation 5. In section VI it is shown that hydrogen produces a polarization of $22\frac{1}{2}\%$ when protons of about 210 Mev are scattered at an angle of about 25° , roughly the parameters of the second scattering. Therefore, the polarization produced in scattering from a first target is approximately determined from the relation $2\epsilon = P_1 P_H$ where 2ϵ is the observed asymmetry in the double scattering, P_1 is the unknown polarization, and P_H is 22% . If P_1 differs from P_H in sign, the asymmetry will be negative, the flux being a maximum at $\phi = 180^\circ$ rather than 0° .

Experimental Results

The procedure followed in measuring the asymmetry in the second scattered proton flux corresponded closely to that in the preceding experiments. The background was evaluated by replacing the $(CH_2)_n$ second scatterer by one of carbon, as before, and amounted to 10-14% of the true p-p counting rate. Only azimuthal angles of 0° and 180° were observed, the 90° - 270° fluxes having served in the preceding experiment merely to demonstrate the correct behavior of flux variation with ϕ .

The data for each element are presented in terms of the directly measured asymmetry, 2ϵ , and the derived quantity, P_1 , the polarization produced in a single collision. The carbon datum from the preceding experiment is included in the table of results (Table IV).

It should be remarked that these data all refer to an incident proton energy of about 230 Mev, a first scattering angle of 18 - 22° and a second angle of about 25° . In using the relation (1) it is assumed that P_2 , the hydrogen polarization, does not vary rapidly over the energy range represented in the beam.

An alternative to using the hydrogen second target as an analyzer is the use of a single element as both first and second scatterers. This method was, in fact, used in the case of carbon and aluminum, in addition to the determination of the polarization produced by these elements using the first method with hydrogen as analyzer. The results from such an experiment with carbon as first and second scatterer were presented in section VII, where it was pointed out that in omitting the recoil proton counter from the second scattering arrangement, reproducibility of results was lost. The experiment with aluminum as both first and second scatterer was performed but once, yielding an asymmetry of $11^{+5}\%$. This corresponds to a polarization in a single scatter of $24^{+4}\%$, which is to be compared with the values $21^{+8}\%$ obtained with the hydrogen analyzer method.

The polarization from deuterium was obtained in a subtraction experiment entirely analogous to the hydrogen polarization experiment. Asymmetries were measured, with hydrogen as analyzer, for carbon first target and $(CD_2)_n$, deuterio-paraffin, first target. The subtraction then gave the polarization of the proton beam scattered from deuterium. The scattering processes contributing to the beam included quasi-p-p, quasi-p-n, and elastic p-d scattering. It is not possible to determine in such a measurement the polarization produced in these processes separately. The quasi-p-p polarization would be expected to be similar to the p-p, modified by the presence of the lightly bound neutron. A measurement of this effect alone, is, in principle, possible by using a CD_2 second target, requiring detection, as in the p-p case, of both scattered protons; the pulse height and angular acceptance of the counters in the second scattering apparatus, however, made separation of the "p-p" and elastic "p-d" events impractical. The experiment was thus necessarily confined to a measurement of the sum of the effects using the subtraction method alone.

With the exception of deuterium, all elements were in natural isotopic abundance.

Discussion

The strong polarization in scattering from carbon, in which about three quarters of the protons are in one spin state provides a polarized protons source for other experiments. Fluxes of 5×10^6 protons per cm^2 per minute were available at our second scattering chamber. With polarized target protons prepared by methods discussed by Rose¹⁶ and Overhauser¹⁷, the triplet and singlet proton-proton scattering might be separated. Since the beam may be slowed in material without appreciable depolarization, nuclear reactions at lower energies might be studied if provisions were made to reduce the energy spread initially present. If the polarization persists to higher energies, studies of meson production from polarized protons may prove of interest.

The nuclear scatterings with which we are dealing here are chiefly internal proton-proton scatters modified in heavier elements by multiple events. The proton-nucleon scattering in deuterium and carbon has been measured as a function of angle and energy by Cladis, Hess and Moyer,¹¹ who found distributions consistent with that predicted by Wolff¹⁹ on the basis of single proton-nucleon collisions within the nuclei and with a reasonable internal momentum distribution. The diffraction scattering studied by Richardson, Ball, Leith and Hadley¹² has a strong forward peak falling off at larger angles, so that for carbon, for instance, at about 20° , the cross section is only a few per cent of that observed²⁰ for all high energy protons from carbon. The multiple scattering within lead nuclei has been studied theoretically by Goldberger. Although his assumed mean free path should be modified, the calculations indicate that the multiple scattering broadens the energy spectrum by relatively small amounts.

There are no theoretical calculations of which we are aware that treat polarization effects in high energy scattering from complex nuclei. The sizable polarization effect observed may be of interest in the study of nuclear forces if suitable theoretical analyses become available.

The rise in polarization from 21% in hydrogen to about 50% in deuterium and the persistence of the 50% level through the light elements to carbon would most simply be explained by a very strong polarization effect due to the neutrons in the nuclei combining additively with the proton effect as for effectively free collisions. It is not clear that this is a proper interpretation even in the loosely bound deuteron. It is a special case since some of the protons are scattered elastically from the deuteron and in that case interference effects between proton scattering from the proton and neutron may be important. On the basis of published p-d scattering results^{11,12} it may be estimated that the ratio of quasi p-p to quasi p-n to elastic p-d contributions at our angle of scatter and incident energy are 1:1:2.

The results of Wouters²² preliminary experiment on polarization effects in p-n scattering may be compared with the indications given by our results. Wouters found an asymmetry of $32 \pm 12\%$ in n-p scattering at 30° laboratory proton angle and within his accuracy no effect at 45° . These were from first scatterings in deuterium and second scatterings in hydrogen. These scatterings are at approximately the supplementary center of mass angle to the one in our experiments for the neutron part of the scattering from deuterium and other elements; in one case an exchange collision occurs, in the other a non-exchange. For a Serber mixture of exchange and ordinary forces these two angles would be equivalent in their polarizations,^{22,14} but in view of the recent evidence²³ from n-p scattering for a different mixture the angles are not equivalent. Wouters also found no polarization effect in the exchange scattering from carbon and lithium. On the basis of a simple nucleon-nucleon collision interpretation it is difficult to see why the polarization effects were found in the proton scattering from nuclei, but not in the neutron scattering.

The downward trend of polarization toward heavier elements may be due to the depolarizing effects of multiple collisions.

The polarization in nuclei may involve other factors than those of a simple impulse nucleon-nucleon interpretation. Theoretical calculations in some detail will be necessary to decide this along with further experiments on the angular and energy dependence of the polarization. One possible enhancement effect in nuclei might occur as follows. The calculations of Goldfarb and Feldman indicate that for tensor forces the chief phases important for the polarization are the P and coupled 3F_2 . A mechanism to suppress the scattering associated with the non-polarizing phases would increase the polarization. Since at this energy the impact parameters for angular momenta

of 2-3 $\hbar$ become as large as one half the internucleon spacing, the higher waves are more probably associated with momentum transfers to more than one nucleon and thus would not yield protons in the top energy range we selected. Modification of the 3F_2 phase by this process might also effect the polarization.

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Figure Captions

- FIG. 1. Plan view of experimental arrangement.
- FIG. 2. Second scattering chamber in cross section.
- FIG. 3. Block diagram of electronic equipment.
- FIG. 4. Profile of scattered beam, as measured by coincidence rate vs. exploratory counter horizontal translation. Counters were 0.3 inches diameter separated by 20 inches. The profile indicates a beam with angular divergence of 1.8° , full width at half maximum.

Table I: Quadruple coincidences per monitor unit normalized to 100 for average over four ϕ angles, for two independent series of runs. Indicated uncertainties due to counting statistics.

ϕ	Carbon 1 st Hydrogen 2 nd				CH ₂ 1 st Hydrogen 2 nd			
	I		II		I		II	
	True	Background	True	Background	True	Background	True	Background
0°	110.8 ⁺ _{-1.4}	13.0	108.6 ⁺ _{-1.2}	6.3	107.1 ⁺ _{-1.5}	6.2	106.3 ⁺ _{-1.6}	6.7
90°	101.0 ⁺ _{-1.7}	9.0	99.4 ⁺ _{-2.0}	5.8	102.2 ⁺ _{-2.6}	5.1	-	
180°	90.1 ⁺ _{-1.2}	7.3	91.4 ⁺ _{-1.1}	5.8	91.6 ⁺ _{-1.4}	4.8	93.7 ⁺ _{-1.5}	5.0
270°	98.8 ⁺ _{-1.8}	9.3	100.6 ⁺ _{-2.2}	7.0	103.4 ⁺ _{-2.6}	4.3	-	

Table II: Comparison of asymmetries for two independent series of runs.

Indicated uncertainties due to counting statistics.

Targets		Run Series	Asymmetry $\frac{2e}{\%}$	Hydrogen Yield, %
First	Second			
Carbon	Hydrogen	I	$20.6^{+2.2}_{-2.2}$	-
		II	$17.2^{+1.6}_{-1.6}$	-
$(CH_2)_n$	Hydrogen	I	$15.5^{+2.2}_{-2.2}$	$.50^{+0.5}_{-0.5}$
		II	$12.6^{+2.2}_{-2.2}$	$.55^{+0.05}_{-0.05}$
Hydrogen (derived)	Hydrogen	I	10.4^{+5}_{-5}	-
		II	8.8^{+5}_{-5}	-
		Combined	$9.6^{+3.5}_{-3.5}$	-

Table III: Derived polarizations from carbon and hydrogen neglecting angle and energy difference in the two scatters. Indicated uncertainties due to counting statistics.

Run Series	I	II	Combined
P_C	$(45^{+13})\%$	$(41^{+11})\%$	$(43^{+8})\%$
P_H	$(23^{+6})\%$	$(21^{+6})\%$	$(22^{+4})\%$

Table IV: Polarization in scattering from several elements. Indicated uncertainties due to counting statistics.

Element	D	Li	Be	B	C	Al	Si	Cu	Ag
Asymmetry with H									
Analysers a)	20^{+3}_{-3}	$22^{+2.5}_{-2.5}$	$21^{+2.5}_{-2.5}$	20^{+3}_{-3}	$18^{+1.5}_{-1.5}$	9^{+3}_{-3}	10^{+2}_{-2}	19^{+3}_{-3}	12^{+5}_{-5}
Derived Polarization in Single Scatter b)	45^{+11}_{-11}	49^{+11}_{-11}	49^{+11}_{-11}	46^{+12}_{-12}	43^{+8}_{-8}	21^{+8}_{-8}	20^{+6}_{-6}	44^{+11}_{-11}	28^{+13}_{-13}

a) Second Scattering from Hydrogen at 27° , First Scattering from Element at 20° .

b) Based on Hydrogen Polarization 22^{+4}_{-4} from Table III.

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FIG. 1. Plan view of experimental arrangement

FIG. 2. Second scattering chamber in cross section.

FIG. 3. Block Diagram of electronic equipment.

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SCATTERED BEAM HORIZONTAL PROFILE

FIG 4. Profile of scattered beam as measured by coincidence rate vs. exploratory counter horizontal translation.