Scattering of Polarized Neutrons from Protons at 350 Mev*

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Asymmetries in neutron-proton scattering have been measured at 350 Mev with a 16% polarized neutron beam. Recoil protons were detected at angles between 10° and 65° in the laboratory, with asymmetries measured to about $\frac{1}{2}$% accuracy. When compared with the results of $p-n$ scattering with polarized protons, the present experiment gives information on the spin dependence of the scattering matrix.

I. INTRODUCTION

SEVERAL successful experiments with high-energy polarized proton beams have been reported recently.[1–3] However, measurements with polarized neutrons have encountered difficulties, mostly associated with the small polarizations ($<20\%$) obtainable from (p,n) reactions in the region of a few hundred Mev.[4–6] Neutron beams having this degree of polarization give scattering asymmetries $[\epsilon=(L-R)/(L+R)]$ which are only a few percent in magnitude, and are therefore difficult to measure accurately. Larger polarizations (50–80%) might be expected for neutrons elastically scattered from light nuclei, since that method has proven so useful for polarizing protons. However, intensity problems are severe if one attempts first to produce neutrons by (p,n) reaction, second to scatter them elastically from carbon, for example, and finally to use the resultant beam for a scattering or production experiment. Hence all neutron experiments to date, including the one reported here, have polarized the neutrons directly in an exchange reaction and worked with small asymmetries.

Our experimental arrangement is shown in Fig. 1. The beam axis AA' is defined by the center of the telescope T and the point P at the center of the steel collimator tube. The target, either T or T', intercepts the internal beam at a radius of 63.4 in. or 67.4 in., respectively, with emitted neutrons observed at 0° or 20° to the incident protons. The beam is collimated by steel and lead located in the shield wall, and is monitored by a triple coincidence telescope counting protons recoiling 30° downward from a Lucite sheet M. The beam is then scattered at S, with recoil protons being observed by counter telescopes north and south of the beam at equal angles θ_n and θ_s.

The plan of the experiment was to compare the south-north asymmetries in the scattering from carbon and hydrogen of the presumably unpolarized beam from target T and the possibly polarized beam from T'.

II. DESCRIPTION OF APPARATUS

Stringent alignment, symmetry, and stability conditions are imposed upon the apparatus by (a) the expected small polarization of the T' beam, and (b) the rapid angular variation of the $n-p$ differential cross section at 300–400 Mev, which gives rise to spurious asymmetries if $\theta_n \neq \theta_s$. A description of the various parts of the apparatus follows (see Fig. 1).

T and T' were 1 in.×1 in.×$\frac{1}{2}$ in. (the $\frac{1}{2}$ in. was in the radial direction) blocks of carbon, with some data being taken with a T' target consisting of a $1\frac{1}{2}$ in.×1 in. ×1 in. chamber constructed of 0.002 in. stainless steel foil and containing D_2O as a target material. The latter target gave a polarization and intensity only slightly larger than those from carbon, and was abandoned because of the possibility of bubble formation (which would move the effective neutron source) and implosion danger. Both T and T' were mounted on probes which could be radially located to ±0.003 in. with the aid of micrometer stops on the outside of the vacuum chamber.

The collimator was built up from seven one-foot lead blocks, bored out and spaced in the shield wall as indicated in Fig. 1. A $\frac{1}{4}$-in. wall×3-in. i.d. steel tube fitting tightly in these blocks served to hold the defining "slit," which was a 2-in. i.d. steel tube six feet long with one end at P. Sighting holes in brass disks fitted in at P and P' were used for setting telescope T along the collimator axis, the disks being removed during the experiment. It was possible to center the telescope on the axis to about 0.003 in. by using the diffraction patterns from the sighting holes.

The alignment of monitor M was not critical, since no absolute counting was done. Proceeding along the beam axis, we next encounter S and S', two points above the scattering table. S was the center of a 0.012-in. diameter hole bored in a carbon block, and S' was the tip of a conical marker, 44 in. from S on the beam axis. The scattering table was a structure of aluminum I-beams, with a semicircle of bent channel supporting the outer ends of the two scattering arms, which were pivoted about S. The two arms were of 2-in.×4-in. Al bar faced with ground $\frac{1}{4}$-in. steel plates on the 2-in. sides

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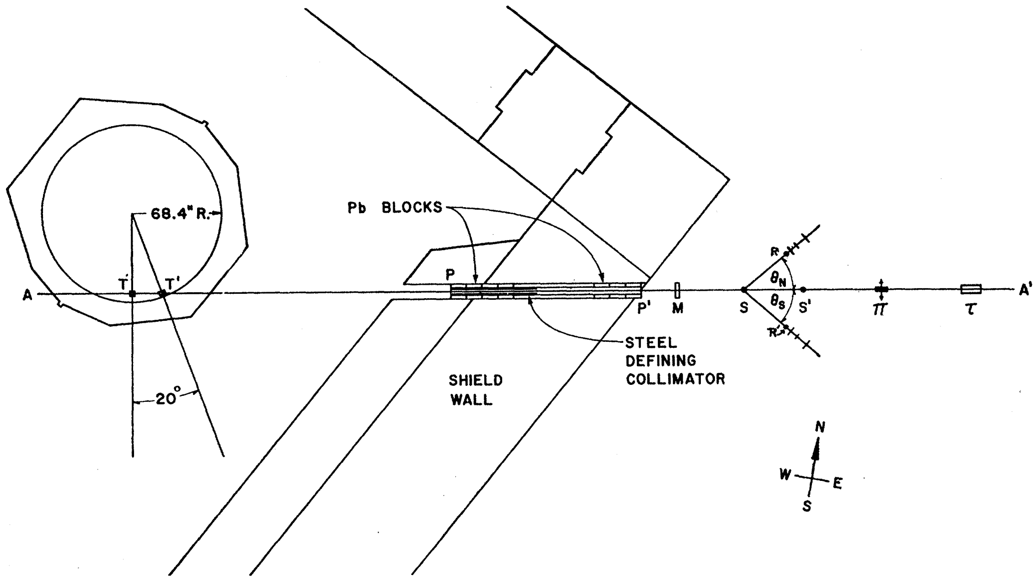

FIG. 1. Experimental layout for 350-Mev polarized or unpolarized neutron-proton scattering.

in order to permit accurate repositioning of the counters. The arms were offset in such a way that counter arrays would look directly at the scattering center S.

Equal angles north and south of the beam were achieved by locating two reference posts on the scattering arms at equal distances from point S, the scatterer center (see Fig. 1). Then two Al bars were clamped together and drilled through so that they would fit snugly over the posts R and S', or R' and S'. The two identically drilled "angle bars" were then separated, and by choosing appropriate holes in each bar equal θ_n and θ_s could be set. Angles from 0°–90° in five-degree intervals were obtainable with these bars.

Levelling screws on the three points of the scattering table rested on a heavy steel base, with the screws being adjusted so that the tops of the scattering arms were three inches below beam height. These arms supported the counter telescope mounts, which were symmetric about the horizontal plane containing the beam. Therefore it was possible to lift counter telescope I, for example, from its supporting arm, rotate it through 180° about its horizontal axis, and place it on the other arm. This is equivalent to rotating I through 180° of azimuth.

The counter telescopes I and II were similar to each other, but no effort was expended to make them identical. Therefore one measurement of asymmetry consisted in counting scattered flux per unit monitor for one of the telescopes south of the beam, and then inverting this telescope and counting flux scattered north of the beam.

The three scintillation counters in a telescope each consisted of a terphenyl-polystyrene plastic scintillator attached to a Lucite light pipe and viewed by an RCA 6199 photomultiplier. The first scintillator to see the scattered particles was $2\frac{1}{8}$ in. wide $\times 4\frac{1}{4}$ in. high $\times 0.2$ in. thick, the second was 2 in. $\times 4$ in. $\times 0.2$ in., the third $2\frac{3}{8}$ in. $\times 4\frac{1}{2}$ in. $\times 0.4$ in. The second counter defined the solid angle, and was usually placed at 70.8 cm from scatterer S, while the first and third counters were 12.8 cm and 21.4 cm in front of and behind the second plastic, respectively. The copper absorber was located between the last two counters, and was adjusted at each angle to keep a 320-Mev low-energy cutoff on the incident neutrons. The efficiency *vs* angle and energy of such telescopes has been reported earlier.[7]

The purpose of using two telescopes was not only to

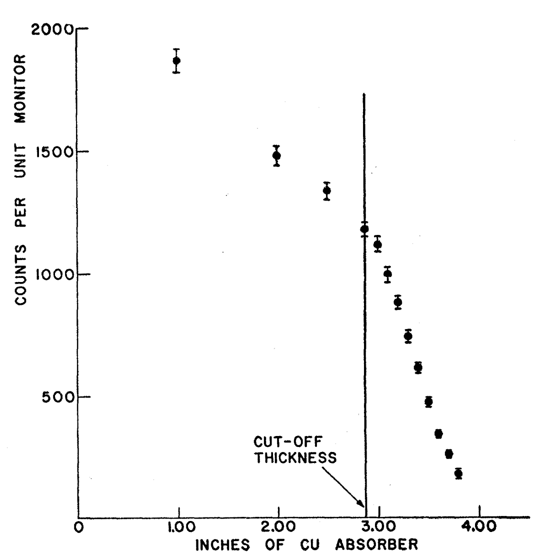

FIG. 2. Differential range curve of proton recoils from hydrogen at 20° to an incident neutron beam produced by 420-Mev protons on D_2O at target position T'. (See Fig. 1.)

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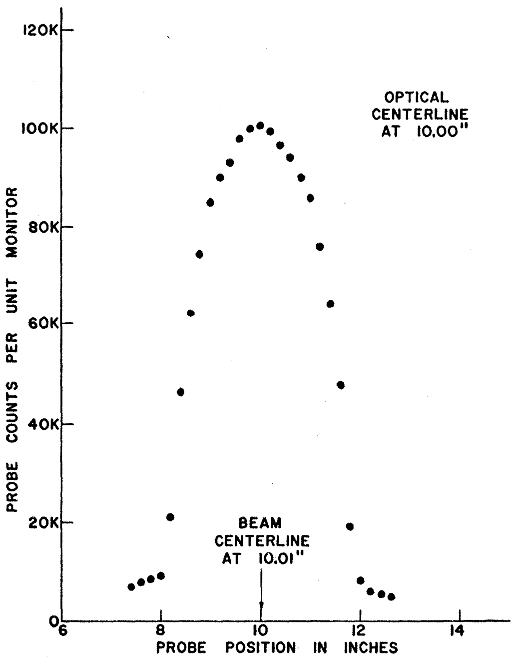

FIG. 3. Beam intensity *vs* probe position obtained for a D_2O target at T'. (See Fig. 1.)

double the rate of accumulating data, but also to provide a check against certain types of electronic drifts. With two telescopes on opposite sides of the beam at all times, a steady drift in the monitor or equal drifts in the two telescope circuits would produce equal and opposite asymmetries in I and II with the unpolarized beam. At first some effects of this type were noticed, but stabilization of the monitor circuits produced asymmetries with the polarized beam which were generally the same for I and II, and which were zero for the unpolarized beam.

The electronic circuits were essentially the same as those used in our earlier work,[7] consisting of fast (7×10^{-9} sec) diode coincidence circuits with associated amplifiers, limiters, and scalers. Differential range curves were taken with a fourth counter in each telescope in anticoincidence with the other three. Addition of a biased diode transfromed the coincidence circuits into anticoincidence circuits for this purpose.

The CH_2 and C scatterers had equal stopping power, and were machined blocks 6 in. high by $1\frac{3}{4}$ in. wide by 0.800 in. and 0.537 in., respectively. The liquid hydrogen targets were constructed of Styrofoam and had an inner liner of 0.002-in. Cu foil defining a useful target volume 4 in. on each edge. Background measurements were made with a similar empty target.

Even after the initial alignment of the scattering table, i.e., placement of S and S' on the beam axis, the process of inverting telescopes and loading them with different amounts of Cu absorber often warped the table and changed the angular setting. For convenience in realigning after each disturbance, two dial gauges attached to the steel base frame were mounted below and near S and S', so that movements relative to the base were easily detected and corrected. Once initial alignment was accomplished, additional angular errors were limited to $\pm0.003/44$. Our aim was to keep the total angular error of alignment to 1′ of arc, and results indicate that this was usually attained.

III. NEUTRON BEAMS

The spectra of neutrons emitted from the various internal targets were badly smeared out in energy, as is illustrated by Fig. 2. This is a differential range curve of protons emitted from liquid hydrogen at 20° to the neutron beam from the D_2O target at T', and shows little indication of a high-energy peak in the neutron spectrum. This is different from the beams emitted at 0° from Be at these energies,[7] and makes observations with "monoenergetic" neutrons rather difficult. However, we found that the Cu absorbers which imposed a 320-Mev lower energy limit on the neutrons left sufficient intensity ($\sim2\times10^4$ cm^{-2} sec^{-1}) of higher energy neutrons for our purposes. Above cutoff (indicated by the vertical line in Fig. 3), the rising efficiency of the counter telescopes gave an effective neutron spectrum peaked at 350 Mev and about 35 Mev wide at half-maximum.

It was important to place T or T' accurately on the axis AA', since otherwise the beam would cut across the collimator at a slight angle, with a resultant skewness about AA' in intensity and/or angular distribution of the neutrons within the beam. Because the beam pene-

TABLE I. Asymmetries from polarized neutrons scattered from hydrogen.

Target θ	Carbon	Carbon	D_2O	D_2O	D_2O	D_2O	Carbon	Carbon
10			1.53±0.98	1.24±0.56		1.88±0.43	1.93±0.35	1.58±0.46
15								2.16±0.44
20	3.89±0.64	3.18±0.63	1.71±0.42	2.33±0.56	3.04±0.47	1.67±0.40		
25								4.71±0.45
30			4.16±1.06	3.50±0.80		3.52±0.53	3.33±0.43	
35								4.02±0.60
40		3.68±1.13			3.01±0.59	4.01±0.76	3.43±0.47	
45								4.45±0.56
50		1.13±1.15				0.50±0.59		
55							−(3.58±0.64)	0.85±0.60
60					−(4.20±0.74)	−(3.18±0.76)		
65							−(4.85±0.63)	−(2.96±0.72)

tration into the target and thus the neutron source shape were not known very precisely, optical sighting was not considered adequate for centering these targets. Instead they were located by means of beam intensity patterns obtained with a probe counter (π in Fig. 1) which scanned the beam about eight feet behind point S. This probe was a plastic scintillant 5 in. high by $\frac{1}{2}$ in. long in the beam direction by 0.18 in. wide, mounted on a photomultiplier and moved across the neutron beam by means of a lathe screw. The centering procedure was to measure intensity at points on the edges of the beam, and then to move T or T' until the centroid fell on the axis AA'. Usually one-half hour sufficed to achieve this to an accuracy of 0.005–0.010 in. Complete traversals of the beam (Fig. 3) were then made to check its symmetry, which was ~1% throughout the useful portion of the beam. The angular spread within the beam was not

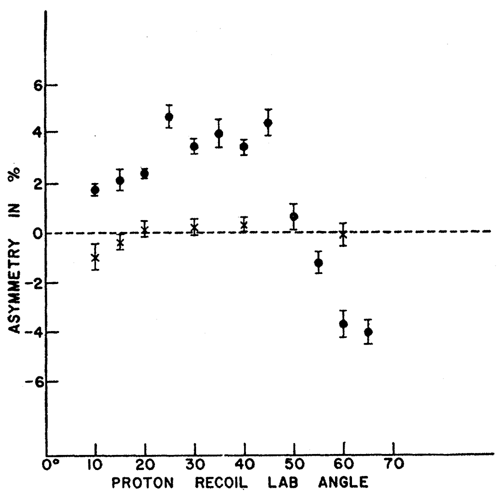

FIG. 4. Asymmetry in 350-Mev $n-p$ scattering *vs* lab recoil proton angle for unpolarized neutrons (crosses) and 16% polarized neutrons (solid circles).

measured, but the zero asymmetries observed when an unpolarized beam was scattered are considered adequate proof that the beam was symmetric in all respects about the axis AA'.

One source of false asymmetry was the stray magnetic field of the cyclotron, which was measured to be 10 gauss in the region of the scattering table. Both from computation and from the small asymmetries measured with the unpolarized beam we were convinced that this was not a major source of error.

On occasion a slight (<1%) asymmetry in small-angle scattering of the T (unpolarized) beam from CH_2 or liquid hydrogen was observed. A check of the alignment usually removed this effect, but during one run it persisted and was removed only by rotating the scattering table about S so as to change the angular positions by 3.5′ of arc. This was probably a valid procedure, because the spurious asymmetry was con-

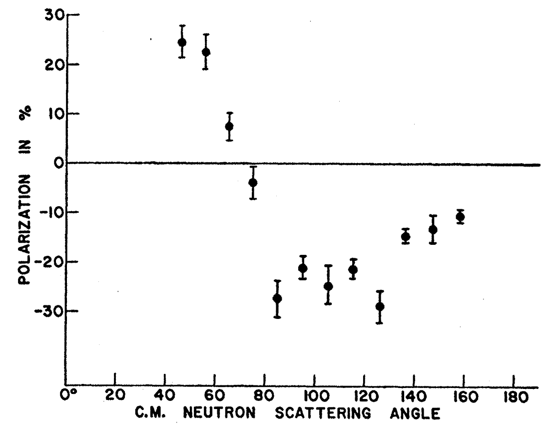

FIG. 5. Polarization *vs* c.m. scattering angle in $n-p$ scattering at 350 Mev.

centrated at small angles (where the $n-p$ cross-section varies rapidly) and was hence of the type to be caused by misalignment of the table. After the run in which this effect appeared, the counter telescopes and table were tightened up and checked and little further trouble was encountered.

IV. RESULTS AND DISCUSSION

Table I shows the asymmetries in $n-p$ scattering of polarized neutrons measured during all our runs. The D_2O data has been reduced to equivalent carbon asymmetries by making use of the measured polarization of the beams (see below). In the early stages of the experiment, when much time was spent investigating possible cause of spurious asymmetry, the (CH_2-C) subtraction was used in obtaining the hydrogen effect because of the greater machining precision attainable for solid scatterers as compared with Styrofoam targets. However, liquid hydrogen is vastly superior as far as background is concerned, and was used for most of the data in Table I.

The mean asymmetries computed from Table I are listed in Column C of Table II. Column B contains the asymmetries for unpolarized neutrons (from target T) scattered from hydrogen or CH_2. The data from these two columns are shown in Fig. 4. Before every run with polarized neutrons, an unpolarized beam was scattered

TABLE II. Asymmetry and polarization *vs* angle for 350-Mev neutron-proton scattering.

A θ_p^{lab}	B Unpolarized $\epsilon(\theta)$ (percent)	C Polarized $\epsilon(\theta)$ (percent)	D $P(\theta_p^{\text{lab}})$ $=-P(\theta_n^{\text{c.m.}})$	E $\theta_n^{\text{c.m.}}$
10°	−(0.94±0.53)	1.73±0.21	0.106±0.014	158°15′
15	−(0.36±0.29)	2.16±0.44	0.132±0.028	147°28′
20	0.11±0.20	2.39±0.20	0.147±0.014	136°45′
25		4.71±0.45	0.289±0.030	126° 8′
30	0.27±0.30	3.48±0.30	0.213±0.019	115°41′
35		4.02±0.60	0.246±0.038	105°20′
40	0.35±0.27	3.43±0.32	0.210±0.022	95° 9′
45		4.45±0.56	0.273±0.032	85° 7′
50		0.63±0.52	0.039±0.032	75°13′
55		−(1.22±0.44)	−(0.075±0.027)	65°29′
60	−(0.13±0.51)	−(3.70±0.53)	−(0.227±0.034)	55°51′
65		−(4.04±0.47)	−(0.248±0.031)	46°21′

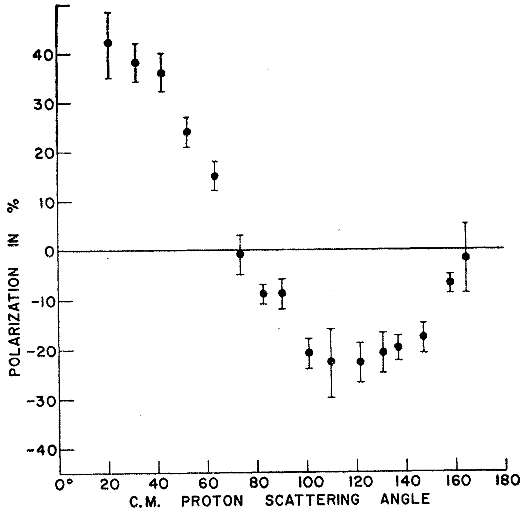

FIG. 6. Polarization *vs* c.m. scattering angle in $p-n$ scattering at 310 Mev.

at 10° or 15°, where spurious asymmetries were expected to be seen most readily. If no asymmetries appeared, we were satisfied that the alignment was correct, and proceeded with the experiment.

Assuming charge symmetry and neglecting the difference in energy between the protons incident on carbon at T' and the neutrons incident on scatterer S, a measurement of beam polarization can be made by measuring the asymmetry in protons recoiling at 20° from carbon at S. In this case $\epsilon=(I_s-I_n)/(I_s+I_n)=P^2$, where P is the polarization. For $P_{20°}{}^{\text{carbon}}$ we thus obtained (0.163±0.007). (Quoted errors are statistical standard deviations from counting only.) Once a carbon detector was calibrated in this way, we could measure $P_{20°}{}^{D_2O}=0.181\pm0.016$. Here we have arbitrarily taken the sign of the polarization as positive.

The asymmetry *vs* laboratory angle observed for the recoil protons in $n-p$ scattering can be converted into polarization *vs* center-of-mass angle for the scattered neutrons by reversing sign, dividing by the beam polarization, and using the kinematic transformations from laboratory to center-of-mass system. The result is plotted in Fig. 5.

One of the main purposes of this investigation was to provide new information about nucleon-nucleon scattering which would be useful in phase-shift analyses. However, the effective energy of this work (350 Mev) is not much higher than that at Berkeley (300 Mev) where $p-n$ scattering has been carried out with polarized protons and deuterium as a "free" neutron target.[8] A comparison of our Fig. 5 and Fig. 6, which displays the data of Chamberlain *et al.*,[9] shows a striking similarity between the results of the two experiments. This similarity may be interpreted as evidence for charge symmetry in nucleon-nucleon scattering. Noting that our polarized neutrons are to be compared with the polarized portons used by the Berkeley group, we have measured $P_{n-p}(\theta)=\text{Tr}M^\dagger M\boldsymbol{\sigma}_n\cdot\mathbf{N}/\text{Tr}M^\dagger M$, while they have measured $P_{p-n}(\theta)=\text{Tr}M^\dagger M\boldsymbol{\sigma}_p\cdot\mathbf{N}/\text{Tr}M^\dagger M$, where M is the $n-p$ scattering matrix. (The notation is that of Wolfenstein and Ashkin.[10]) The equality of the two results indicates that M is symmetric in its dependence on $\boldsymbol{\sigma}_n$ and $\boldsymbol{\sigma}_p$, at least insofar as the nuclear force contribution is concerned. The electromagnetic interaction contributes a negligible amount to the scattering for the angles investigated in the two experiments.

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[9] We wish to thank the Berkeley group for communicating their detailed results before publication.

[10] L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952).