Asymmetry in 143-Mev *pn* Scattering*

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A beam of 145-Mev protons of polarization 69±2% was scattered from liquid deuterium. *pn* scattering events were identified by a coincidence method. The asymmetry in the scattering was measured. These data can be compared with polarization in free *np* scattering at the appropriate angles.

INTRODUCTION

EXTENSIVE measurements on *pp* scattering at about 145 Mev will probably yield definitive information on the triplet isotopic spin states of the two-nucleon system. A study of *np* scattering will yield in addition information on the singlet isotopic spin system. This experiment, the first of a series, measured the polarization parameter[1] *P* which measures the polarization or the asymmetry in *np* scattering.

Some previous measurements have been made at 95 Mev[2] and 150 Mev,[3] using neutron beams of 8 and 15% polarization, respectively. In order to overcome the difficulties of working with a beam of such low polarization, we adopted a method first used at 310 Mev,[4] to scatter a polarized proton beam inelastically from deuterium, and to identify those events which correspond to scattering from the bound neutron. The asymmetry of these events was measured and equated to the asymmetry in free *np* scattering.

It is necessary to be sure that this scattering from bound neutrons correctly represents the free-particle scattering. We have satisfied ourselves of this by scattering protons from the bound proton in the deuteron. The detailed results of this study will be presented in a forthcoming paper. Meanwhile we state the following conclusions; that if we include only events such that the "spectator" particle (a proton in the present case) is left with an energy of less than 1 Mev, the polarization is within 10% of the free-particle value with no deviation observed. In this experiment the spectator particle always had an energy of less than 1 Mev, and each of the interacting particles had in the most unfavorable case (40° c.m.) an energy of greater than 17 Mev. In addition one check was made with a larger value for the spectator particle energy with no significant difference in the result.

The desired events were separated by identifying high-energy scattered neutrons in coincidence with scattered protons and the energy of the protons was measured. It is easy to show that the kinematics of the reaction is thereby determined.

APPARATUS

The polarized proton beam was obtained in the same manner as other experiments at Harvard[4] (Fig. 1). Special care was taken in the location of the defining slits and nearby shielding, since it transpired that most of the background neutrons came from protons striking these slits. The final arrangement is shown in Fig. 2. A beam flux of 2×10^7 protons/sec was obtained through a slit 1 inch wide by $2\frac{1}{8}$ in. high. Between this slit and the target were placed antiscattering slits designed to prevent all slit-scattered protons, and as many neutrons as possible, from reaching the counters.

The beam polarization was determined by measuring the asymmetry of elastic scattering from carbon at 15° lab. The measured asymmetry of 0.480±0.015 implies a beam polarization of 0.69±0.02 which is consistent with other measurements of the beam polarization.[5]

The average range of the protons in polyethylene was 14.1 g/cm². Using the range-energy curves of Rich and Madey[6] we deduce an average beam energy of 147 Mev, an average energy of 145±1 Mev at the center of the target. The effective *pn* scattering energy was 143±1 Mev; the difference is due to the binding in the deuteron.

The liquid deuterium target was designed and built by Postma[7] who describes it in some detail. The target cell was a vertical cylinder 3 inches high by 1.8-inch diameter of 0.002-inch Mylar (trade mark of E. I. duPont deNemours and Company) filled with liquid deuterium. Also, in the beam was a heat shield of 0.0003-in. aluminum and an outer wall to the vacuum system of 0.003-in. Mylar. These contributed a negligible amount to the scattering.

The beam was monitored by a Faraday cup, 12 inches in diameter, which collected the protons after they had passed through the target. Additional monitoring was provided by a fixed counter telescope detecting protons above 100 Mev scattered upwards through 20°.

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[1] L. Wolfenstein, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1956), vol. 6, p. 43.
[2] G. H. Stafford, C. Whitehead, and P. Hillman, Nuovo cimento **5**, 1589 (1957).
[3] A. Roberts, J. Tinlot, and E. M. Hafner, Phys. Rev. **95**, 1099 (1954).
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[5] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and Richard Wilson, Ann. Phys. **2**, 299 (1958).
[6] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished).
[7] H. Postma, thesis, Harvard University, 1959 (unpublished).

The over-all counter layout is shown in Fig. 2. The proton telescope consisted of 2 thin plastic scintillation counters followed by a total absorption scintillation counter: The thin counters were $\frac{1}{8}$-inch thick Pilot Chemical plastic scintillator glued to Lucite light pipes about 5 inches long which conducted the light into the face of RCA 6810 photomultipliers. The absorption crystal was a 3-inch diameter×6-inch long scintillator plastic glued to a tapered 10-inch long light pipe which conducted the light onto the face of an RCA 6810 photomultiplier. The energy resolution of this counter was 4% (full width at half maximum) at 147 Mev.

The neuteron counter and discriminator was a tank counter of the type discussed by Thresher, Van Zyl, Voss, and Wilson.[8] The details of its construction are shown in Fig. 3. The scintillation solution consisted of: 2 liters phenylcyclohexane, 6-g *p*-diphenyl benzene, and 20-mg diphenylhexatriene. The counters were mounted on aluminum channels which rolled upon the floor about a pivot which was carefully positioned under the proton beam. The angle of scattering was determined by a bar which fixed the distance between a pin on the channel holding the counters and a pin fixed to the floor 55 inches downstream of the target. Accurate positioning of the counters was further facilitated by two machinist's levels fastened to each mounting channel, one to level each telescope radially and the other azimuthally. Dial indicator tests showed that the counter position was reproducible to ±0.010 inch.

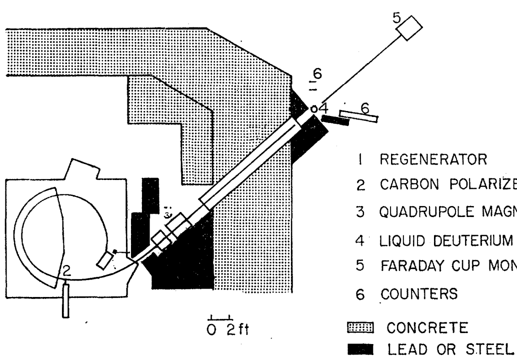

FIG. 1. Over-all layout.

EXPERIMENTAL PROCEDURE

The target and pivot for the counter arms were each positioned to $\pm\frac{1}{32}$ inch of their correct positions with respect to the beam using x-ray film exposures. The "zero"-degree angle of the counters was determined by sweeping them through the incident beam and observing the integrated output. The zero-degree angle was determined to ±0.03 degree for each counter arm.

A block diagram of the electronic circuits is shown in Fig. 4. The output of the neutron counter was fed to a discriminator using an EFP60 secondary emission tube. Its dead time was about 100 nanoseconds. The discriminated output was fed into a triple coincidence circuit of the type described by Garwin,[9] where a coincidence with the two proton telescope counters was formed. The resolving time of the coincidence was 32 nanoseconds (full width) which was long enough to ensure that no counts were missed by the distribution of particle velocities. The output of the triple coincidence circuit opened a linear gate for 0.2 μsec, through which the signal from the total absorption scintillator passed and was fed to a pulse-height analyzer.

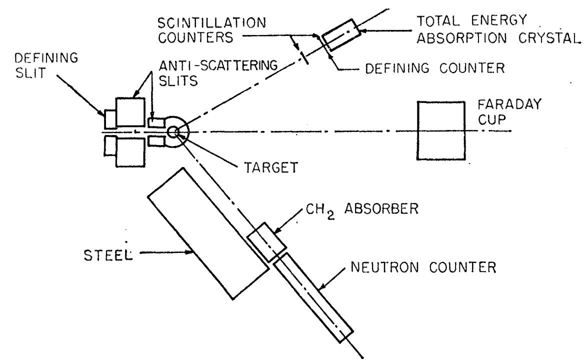

FIG. 2. Counter layout.

EXPERIMENTAL ERRORS

The only significant background in this experiment was found to be random coincidences between protons counted by the proton telescope and neutrons counted by the neutron counter; many of these latter neutrons did not come from the target but came from protons striking the beam pipe of defining slit as discussed earlier. These random coincidences were measured by delaying the output of either the neutron counter or the proton telescope 90 nanoseconds with respect to the other; it made no difference which was delayed. The random rate was consistent with the known singles rates and the resolution time. The random rate was 30% of the over-all counting rate at the 40° c.m. point, and less than 15% at all other points. The asymmetry of the random coincidence counts tended to follow that of the genuine coincidence so no systematic error is introduced by the random coincidence subtraction.

There are many contributions to the alignment error.

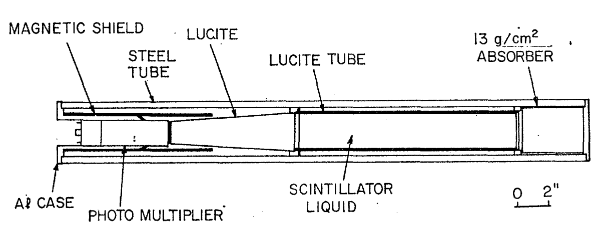

FIG. 3. Neutron counter.

[8] J. J. Thresher, C. P. Van Zyl, R. G. P. Voss, and Richard Wilson, Rev. Sci. Instr. 26, 1186 (1955).

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

TABLE I. *pn* polarization data. $\theta_{c.m.}$ = center-of-mass scattering angle; θ_n = laboratory angle of neutron counter; θ_p = laboratory angle of proton telescope; P = polarization parameter.

$\theta_{c.m.}$	θ_n	θ_p	P
41°	67.5°	20°	+0.475±0.039
51°	62.5°	25°	+0.495±0.017
62°	57.5°	30°	+0.480±0.016
72°	52.5°	35°	+0.425±0.021
82.5°	47.5°	40°	+0.272±0.021
92.5°	42.5°	45°	+0.160±0.015
108°	35°	52.5°	+0.015±0.016
118°	30°	57.5°	−0.020±0.016
(53°)	57.5°	25°	+0.520±0.034

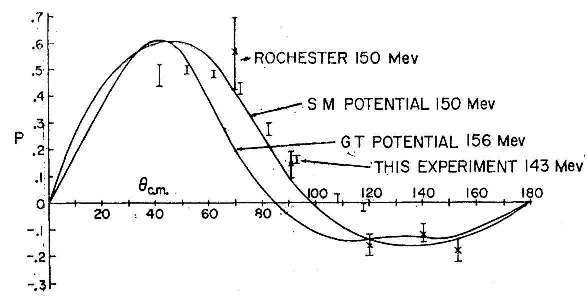

FIG. 5. P for *np* scattering.

The most serious arises from the dependence of the inelastic *pd* scattering cross section on the included angle between the scattered proton and the scattered neutron. The apparatus did not fix this quantity directly; each counter was independently aligned to the beam, so the alignment errors add. Fortunately at the 87.5° angular separation of the counters the cross section is a maximum. The over-all alignment error is less than ±0.008 in the polarization at any angle.

The energy discrimination of the neutron counter was varied by adjusting the counter voltage holding the discriminator voltage constant at about 10 volts. This discrimination level was adjusted at each angle setting of the counters to optimize the relation between counting rate and random rates. The threshold varied from about 20-Mev ionization loss at large scattering angles to about 6 Mev at the small scattering angles, this was between $\frac{1}{3}$ and $\frac{1}{4}$ of the neutron energy. Over this same range the counting efficiency for these chosen discrimination levels varied from about 25% at large to 6% at small scattering angles. The errors in the asymmetry results from threshold drifts in the neutron counter were verified to be negligible.

To avoid systematic errors the apparatus was changed left to right at least once every hour. At each setting of the counters one run of real coincidence counts was followed by one of the random coincidence counts which was again followed by one run of real counts. The counters were then interchanged and the same done in the inverted position of the apparatus. At each angle a total of from 24 to 36 runs of data were collected. Chi square tests showed all data to be statistically consistent.

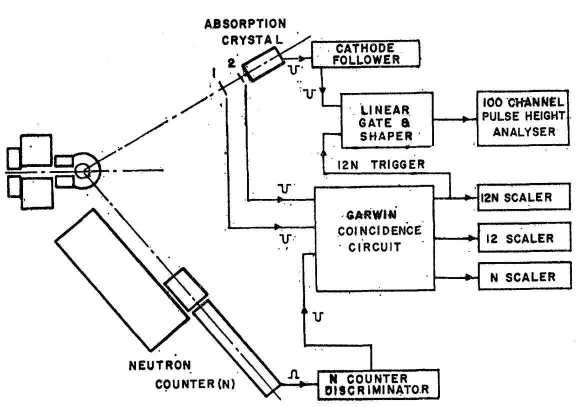

FIG. 4. Block diagram of the electronic circuits.

Calculations show that no significant errors are caused by the variation of counting efficiency of the neutron counter with energy, dead time losses, or bias level shifts or pile up in the neutron counter due to changing counting rate.

At the larger c.m. angles up to 5% of the protons which are scattered off the proton bound in the deuteron stop in the vicinity of the neutron counter and produce neutrons which are subsequently counted as *pn* events. Using the neutron production cross sections of Hoffman and Strauch[10] and the known asymmetries in *pp* scattering, it is easily shown that the effect of these events on our asymmetry measurement is less than ±0.008 in the polarization.

RESULTS

The results of the experiment are tabulated in Table I and are plotted in Fig. 5. The error bars include systematic, as well as statistical errors. Figure 5 depicts also the results of the early Rochester experiment on free *np* polarization as well as the predictions of the phenomenological potentials of Gammel and Thaler[11] and that of Signell and Marshak.[12]

Also included in Table I is a measurement taken at an included angle between the proton and neutron of $82\frac{1}{2}$° instead of the optimum $87\frac{1}{2}$°. The spectator particle then has an average energy of 0.75 Mev as compared with the usual 0.38 Mev: This has made no appreciable difference in the polarization, lending further support to our contention that this data can be treated as free *pn* scattering.

ACKNOWLEDGMENTS

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[10] J. A. Hofmann and K. Strauch, Phys. Rev. **90**, 449 (1953).
[11] J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 1337 (1957).
[12] P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958).