an appreciable cross section, but appears most strongly in multibody final states which are difficult to treat in a quantitative way.

Other meson and baryon resonances are observed, but only in the observed quasi-two-body states are the production mechanisms amenable to analysis. These two-body states (ΞK, ΞK^*, $\Lambda\phi$, $Y_0{}^*\phi$) are peripheral, indicating the importance of single-particle-exchange mechanisms.

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Proton-Neutron Triple Scattering at 425 MeV. I*

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The proton-neutron triple scattering parameters P, D, R, and A have been measured at lab angles of 20°, 30°, and 42° at 425-MeV incident proton energy. Polarized protons were scattered from neutrons in deuterium, and the final proton polarization was measured with a carbon plate wire-spark-chamber system. The recoil neutrons were detected. p-p quasielastic scattering from deuterium was also studied at 30° and 42° as a check on the impulse approximation.

I. INTRODUCTION

THIS paper represents the first in a planned series of experiments applying wire-spark-chamber techniques to the study of proton-neutron triple scattering at 425 MeV. A polarized proton beam was scattered from neutrons in deuterium, and the final transverse proton polarization was analyzed by scattering from carbon. A polarimeter with six wire spark chambers and an on-line computer recorded the azimuthal scattering distribution from the carbon. This polarimeter has been previously used in p-p triple-scattering studies at the same energy.[1] A complete discussion of the wire-chamber system and the computer programs can be found in Ref. 1. The apparatus was modified for p-n scattering by using a liquid deuterium target and counting the recoil neutrons with a large-volume plastic scintillator shielded by an anticoincidence counter.

High-energy p-n triple-scattering data are very scarce. Except for measurements of R at 600 MeV, only the differential cross section and polarization have been measured at energies above 210 MeV.[2] The knowledge of isoscalar ($I=0$) amplitudes in nucleon-nucleon scattering is therefore limited. The phenomenological situation has recently been discussed by MacGregor, Arndt, and Wright,[3] who performed a phase-shift fit to existing data at 425 MeV. These authors emphasized the qualitative nature of the $I=0$ phase shifts obtained. This experiment was undertaken to improve the knowledge of the isoscalar nucleon-nucleon interaction.

II. EXPERIMENTAL PROCEDURE

The final proton spin after p-n scattering can be expressed in the same form as for p-p scattering, using the polarization P and the Wolfenstein parameters D, A, R, A', and R'. Thus,

$$\langle\boldsymbol{\sigma}\rangle I_p(\theta,\phi)=I_0(\theta)[(P+D\langle\boldsymbol{\sigma}_i\cdot\hat{n}_i\rangle)\hat{n}_f +(A\langle\boldsymbol{\sigma}_i\cdot\hat{k}_i\rangle+R\langle\boldsymbol{\sigma}_i\cdot\hat{s}_i\rangle)\hat{s}_f +(A'\langle\boldsymbol{\sigma}_i\cdot\hat{k}_i\rangle+R'\langle\boldsymbol{\sigma}_i\cdot\hat{s}_i\rangle)\hat{k}_f]. \quad (1)$$

This equation is written in the laboratory frame. P, D, A, R, A', and R' are functions of the laboratory scatter-

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[1] P. Limon, L. Pondrom, S. Olsen, P. Kloeppel, R. Handler, and S. C. Wright, Phys. Rev. **169**, 1026 (1968). There are some errors in this paper. In Eq. (3) the right-hand side should be multiplied by $\hat{n}$. In Eq. (6) each ϵ_D equation should be multiplied on the right by P_3.

[2] A complete listing of p-n data with references as of April, 1968 has been made by M. H. MacGregor, R. A. Arndt, and R. M. Wright, Lawrence Radiation Laboratory Report No. UCRL-50426 (unpublished).

[3] M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. **173**, 1272 (1968).

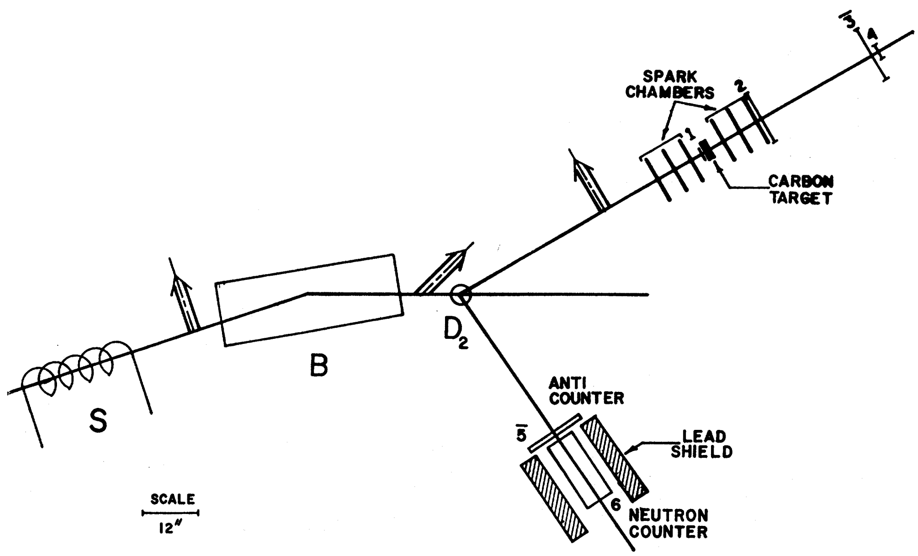

FIG. 1. Plan view of the 30° left p-n scattering geometry. The solenoid S is shown schematically, and double arrows are drawn in to indicate proton spin directions. The solenoid polarity is plus for left spin rotation. The bending magnet, liquid deuterium target, neutron counter and spark chamber polarimeter are shown to scale. The proton defining counter, No. 1, subtended a space angle of 3°. The p-n trigger was ($1\ 2\ \bar{3}\ \bar{5}\ 6$). Counter 4 was used for alignment checks.

ing angle θ and bombarding energy E. $I_p(\theta,\phi)=I_0(\theta)\times(1+P\langle\sigma_i\cdot\hat{n}_i\rangle)$. The unit vectors are defined in terms of $\mathbf{k}_i$ and $\mathbf{k}_f$, the initial and final proton momenta in the lab, as follows:

$$\hat{n}_i=(\mathbf{k}_i\times\mathbf{k}_f)/|\mathbf{k}_i\times\mathbf{k}_f|=\hat{n}_f;\quad \hat{s}_i=\hat{n}_i\times\hat{k}_i,\quad \hat{s}_f=\hat{n}_f\times\hat{k}_f.$$

In this experiment final polarization components along $\hat{k}_f$ were not measured.

A typical geometry is shown in Fig. 1. The solenoid S and bending magnet B_1 were used to prepare the initial spin at 45° to the incident momentum $\mathbf{k}_i$, as was done in Ref. 1. The final-state spin components along $\hat{n}_f$ and $\hat{s}_f$ were simultaneously measured, and referred to as left-right asymmetry ϵ and up-down asymmetry δ. Data were taken with solenoid polarity plus (left spin rotation), minus (right spin rotation), and solenoid off for each setup. This technique of taking data allowed the elimination of possible geometrical biases inherent in the polarimeter. For a given p-n scattering angle θ both a left-scattering ($\hat{n}_f$ up) and a right-scattering ($\hat{n}_f$ down) geometry were studied, leading to six measured quantities for the four unknowns P, D, R, and A. To express the unknowns in terms of the measured asymmetries, a right-handed coordinate system $(\hat{x},\hat{y},\hat{z})$ was defined with respect to the wire-spark-chamber analyzer. The z axis was parallel to the axis of the spark-chamber system and directed along the average proton momentum $\hat{k}_f$. The y axis was up, parallel to $\hat{n}_f$ for left scattering as in Fig. 1, and antiparallel for right scattering. The average azimuthal asymmetry measured by the wire chambers could then be expressed as $N(\phi)=1+\epsilon\cos\phi+\delta\sin\phi$. From Eq. (1) it follows that for the geometry of Fig. 1 and solenoid + the following asymmetries would be expected:

$$\begin{aligned}\epsilon&=PP_3,\\ \delta&=-(P_1P_3/\sqrt{2})(A+R).\end{aligned}\qquad(2)$$

Reversing the solenoid changed the sign of the δ term. With solenoid off, $\delta=0$ if parity is conserved and there are no geometrical biases, and

$$\epsilon=\left(\frac{P+DP_1}{1+PP_1}\right)P_3.\qquad(3)$$

In these equations P_1 is the incident proton polarization, given by $P_1=0.535\pm0.025$;[4] and P_3 is the average analyzing power of the carbon target at the appropriate proton energy. For a right-scattering configuration, since the spin-analyzing coordinate system was fixed relative to the spark chambers, the appropriate formulas for solenoid + are

$$\begin{aligned}\epsilon&=-PP_3,\\ \delta&=(P_1P_3/\sqrt{2})(A-R),\end{aligned}\qquad(4)$$

and with solenoid off, $\delta=0$,

$$\epsilon=-\left(\frac{P-DP_1}{1-PP_1}\right)P_3.\qquad(5)$$

To ensure that the trigger protons truly scattered from neutrons in the deuterium, a coincidence was required between the proton and the recoil neutron. The neutron counter was a cylinder of plastic scintillator 6 in. in diam and 15 in. long, or approximately 38 g/cm² of CH. A $10\times18\times\frac{1}{2}$-in. counter was placed in front of the neutron counter as an anticoincidence for neutrons. To count p-p quasielastic scattering from deuterium, this front counter was placed in coincidence. The gain of the neutron counter was adjusted to keep the p-n accidentals rate below 5%. The quasielastic scattering was studied at $\theta=30°$ by keeping the proton telescope fixed and scanning the recoil neutron beam in space. The re-

[4] N. E. Booth (private communication).

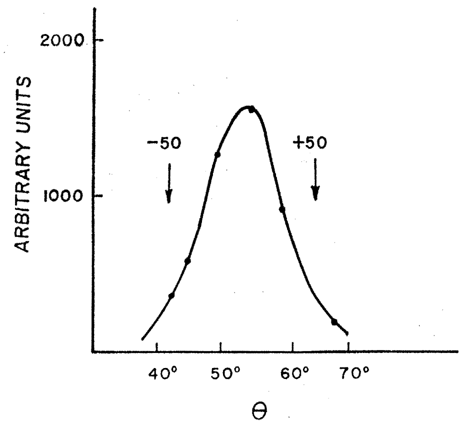

FIG. 2. Neutron space scan for protons at 30° in the laboratory. The expected free p-n angle is 54° 40′. The neutron counter telescope was 5° wide in space during this scan. The arrows at ±50 represent expected neutron recoil angles if the proton scatters at 30° and the target neutron momentum is ±50 MeV/c along the incident beam direction.

sult of this scan is shown in Fig. 2. Note that the expected neutron recoil angles for Fermi momenta of ±50 MeV/c bracket the observed quasielastic peak. During data taking, the neutron counter subtended ±5° about the center of this peak, corresponding roughly to extreme Fermi momenta of ±25 MeV/c for the target neutron, or a spread of ±14 MeV in energy in the p-n center-of-mass system. The neutron counter subtended ±10° and ±7° at $\theta=20°$ and $\theta=42°$, respectively. Thus the kinematic constraints were fairly tight, limiting the data to an almost-free neutron target, if one accepts the impulse-approximation treatment. Final state interactions of the type discussed by Thorndike[5] were not taken into account. As a further check the quasielastic p-p triple scattering parameters were measured at $\theta=30°$ and $\theta=42°$ to compare with the

TABLE I. Asymmetries obtained for the three laboratory angles. For solenoid on, the solenoid + and − values have been combined, $\delta=\frac{1}{2}(\delta_+-\delta_-)$. There was no evidence of geometrical bias between δ_+ and δ_-. The errors are statistical standard deviations. Because of a short in the solenoid at full current, the 42° data were taken at half current, giving a combination of P and D in the ϵ terms for both solenoid on and solenoid off, and reducing the δ asymmetries by $\sqrt{2}$.

θ	Sol.	δ	ϵ	N
20° left	On	−0.173 ±0.008	+0.183±0.008	28 000
20° left	Off	+0.005 ±0.013	+0.350±0.013	12 000
20° right	On	+0.074 ±0.007	−0.158±0.007	38 000
20° right	Off	−0.006 ±0.011	+0.054±0.011	18 000
30° left	On	−0.237 ±0.008	+0.068±0.008	28 000
30° left	Off	+0.0016±0.011	+0.319±0.011	14 000
30° right	On	+0.047 ±0.008	−0.050±0.008	31 000
30° right	Off	+0.0000±0.012	+0.208±0.012	14 000
42° left	On	−0.145 ±0.008	+0.087±0.008	34 000
42° left	Off	−0.032 ±0.014	+0.123±0.014	10 000
42° right	On	−0.001 ±0.007	+0.164±0.007	40 000
42° right	Off	−0.005 ±0.012	+0.235±0.012	14 000

[5] E. H. Thorndike, Rev. Mod. Phys. 39, 513 (1967).

TABLE II. Calibration data. The quantity $P_1P_3(E)$ was measured in the direct beam, varying the energy with aluminum absorbers. The thickness of the carbon scatterer in the polarimeter was decreased from 3 to 2 in. for the 200-MeV data. The angle θ is the appropriate p-n laboratory scattering angle corresponding to the energy E. The errors are statistical standard deviations.

E (MeV)	θ	P_1P_3	Carbon thickness (in.)
425	0°	0.179±0.005	3
365	20°	0.267±0.007	3
305	30°	0.298±0.007	3
210	42°	0.250±0.007	2

free p-p data. As will be seen below, the agreement is satisfactory.

The spark-chamber system was triggered on a p-n scatter followed by a p-carbon scatter in the polarimeter through an angle greater than 5°. With 5×10^7 protons/sec incident on the 1.9-g/cm^2 liquid deuterium target the trigger rate was typically 4/sec. The on-line program analyzed each event as it occurred and selected acceptable events. The event selection is discussed in detail in Ref. 1. The major reject categories

TABLE III. Triple-scattering parameters for quasielastic p-n scattering from deuterium at 425 MeV. The errors are statistical standard deviations. $\bar{\theta}$ is the angle in the p-n center-of-mass system.

θ	$\bar{\theta}$	P	D	R	A
20°	44°	0.347±0.020	0.840±0.035	0.262±0.030	0.655±0.031
30°	65°	0.110±0.010	0.886±0.034	0.449±0.029	0.671±0.031
42°	90°	−0.104±0.012	0.721±0.031	0.548±0.040	0.548±0.040

were wire-chamber misfires, or incident or scattered proton angle out of range with respect to the polarimeter axis. About 15% of the triggers were acceptable events. For each acceptable event the polar and azimuthal angles θ_c and ϕ for the carbon scatter were calculated and an event was added in the appropriate location in a θ_c-ϕ matrix, which divided θ_c between 5° and 20° into 10 equal bins and ϕ between 0° and 360° into 20 equal bins. Every 2000 acceptable events, the program calculated $N(\phi)=1+\epsilon\cos\phi+\delta\sin\phi$ averaged over θ_c, and calculated a χ^2 value for the fit.

TABLE IV. Triple scattering parameters for quasielastic p-p scattering from deuterium compared with previous free p-p data at the same energy.

θ	Target proton	P	D	R	A
30°[a]	bound	0.258±0.019	0.65 ±0.06	0.476±0.039	0.377±0.039
30°[b]	free	0.262±0.013	0.599±0.015	0.498±0.016	0.296±0.013
42°[a]	bound	···	0.67 ±0.04	···	···
42°[c]	free	···	0.67 ±0.10	···	···

[a] This experiment.
[b] Reference 1.
[c] Reference 6.

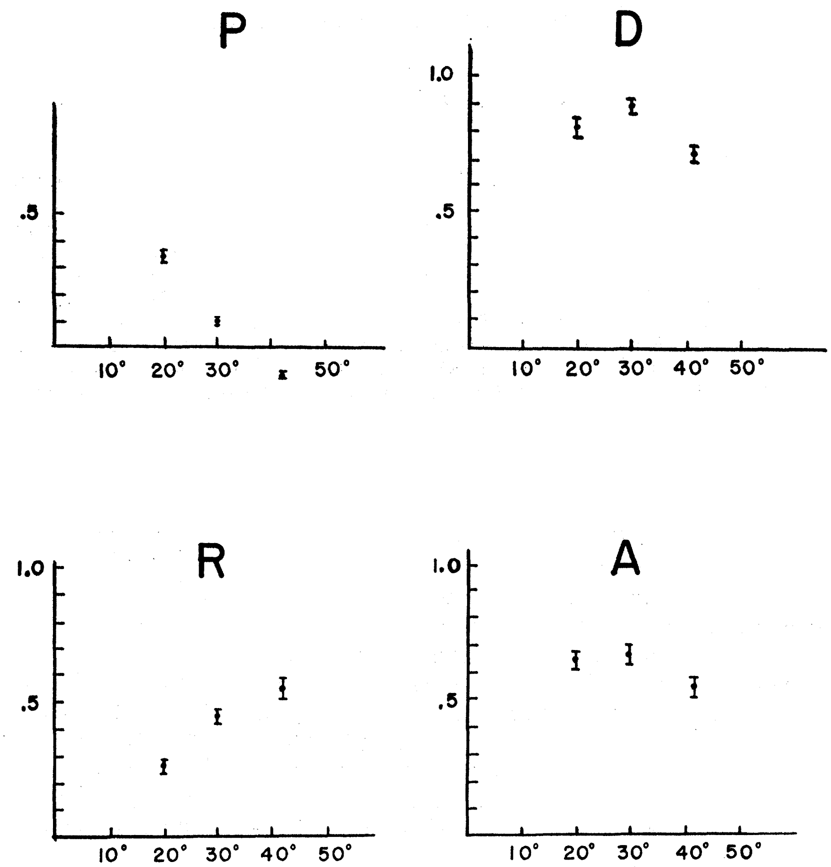

FIG. 3. Parameters P, D, R, and A for p-n scattering at 425 MeV. The abscissa is the laboratory proton angle in each case.

Three laboratory p-n scattering angles were studied: 20°, 30°, and 42°. Between 10 000 and 20 000 acceptable events were obtained at each angle for solenoid plus, minus, and off. From Eqs. (2)–(5) it is apparent that the product P_1P_3 must be known to find R and A, and P_1 and P_3 must be separately known to find P and D. The product P_1P_3 was studied as a function of proton energy by placing the polarimeter in the direct proton beam and degrading the energy with aluminum absorbers. The value of P_1 quoted above was then used to find P_3.

III. RESULTS

The asymmetries obtained at the three angles are shown in Table I. No statistically significant geometrical biases favoring up over down or right over left were found in the data. The sensitivity P_1P_3 (E) is shown in Table II. The combination of these results according to Eqs. (2)–(5) was a straightforward task. The δ numbers with solenoid on for the left and right sides at a given θ gave two equations for the two unknowns A and R. The ϵ numbers for the left and right sides were treated separately, giving independent results for P and D. In each case these results were consistent within the statistical errors, and were combined to give the final answers. Table III lists the results for p-n triple scattering. These results are presented graphically in Fig. 3. In Table IV the p-p scattering parameters measured in deuterium are compared with the results of Refs. 1 and 6 where the same parameters were measured in hydrogen. The agreement is quite satisfactory.

ACKNOWLEDGMENTS

We wish to thank E. H. Molthen for efficient operation of the Chicago cyclotron. J. Barney constructed much of the electronics, and J. Lippmann helped during the run.

[6] R. Roth, E. Engels, S. C. Wright, P. Kloeppel, R. Handler, and L. Pondrom, Phys. Rev. **140**, 1533 (1965).