# Spin-Spin Forces in 6-GeV/$c$ Neutron-Proton Elastic Scattering

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Measurement was made of $d\sigma/dt$ for $n_{\uparrow}+p_{\uparrow}\rightarrow n+p$ at $P_{\perp}^2=0.8$ and $1.0$ (GeV/$c$)$^2$ at 6 GeV/$c$. The 6-GeV/$c$ 53%-polarized neutrons from the 12-GeV/$c$ polarized deuteron beam at the Argonne zero-gradient synchroton were scattered from our 75%-polarized proton target. Both spins were oriented perpendicular to the scattering plane. We found large unexpected spin-spin effects in $n$-$p$ elastic scattering which are quite different from the $p$-$p$ spin-spin effects.

The zero-gradient synchrotron (ZGS) polarized proton beam allows measurements of pure-initial-spin-state cross sections in proton-proton scattering. Large and quite unexpected spin-spin effects were discovered in proton-proton elastic scattering. At small $P_{\perp}^2$ these effects are fairly small but have considerable structure,[1] while at large $P_{\perp}^2$ they become very large.[2] Last fall the ZGS staff accelerated the first polarized deuteron beam to high energy.[3] Using the 6-GeV/$c$ polarized neutrons in these 12-GeV/$c$ deuterons, we obtained the first high-energy measurement of spin-spin forces in $n$-$p$ elastic scattering.

The polarized deuterons originated in the ZGS polarized ion source, which emitted 10 $\mu$A of 20-keV deuterons with a polarization of about 55%. The polarized ion source was converted to deuteron operation by replacing the $H_2$ gas with $D_2$ in the gas bottle and modifying the rf transition stage.[3] The synchronization of the linac was modified to allow for the velocity-energy relation of deuterons in the 750-keV to 50-MeV range. The main-ring injection synchronization also had to be readjusted. In the few weeks available for converting the ZGS to a deuteron accelerator all tuning conditions could not be fully optimized. Nevertheless, the ZGS staff was able to accelerate about $10^9$ deuterons per pulse to 12 GeV/$c$.

Depolarizing resonances are a problem in polarized-deuteron acceleration. The energy, $E$, of the $k$th intrinsic depolarizing resonance is given by

$$(\tfrac{1}{2}g-1)E/m=\pm k\pm\nu_y, \quad (1)$$

where $m$ is the accelerated particle's mass, and $g$ is its $g$ factor. The quantity $\nu_y$ is the vertical tuning value, which is 0.80 for the ZGS. For a proton $(\frac{1}{2}g-1)$ is 1.793 while for a deuteron it is $-0.143$. Thus, the deuteron's $(\frac{1}{2}g-1)$ factor is 12.5 times smaller than the proton's. Moreover, the deuteron's mass is about twice the proton's mass. Thus, each $k\pm\nu_y$ depolarizing resonance occurs at an energy which is about 25 times higher for deuterons than for protons. The first intrinsic proton resonance, $4-\nu_y$, which occurs at 1.39 GeV/$c$ for protons, would occur at 35 GeV/$c$ for deuterons. The first imperfection resonance occurs when $E$ satisfies

$$(\tfrac{1}{2}g-1)E/m=\pm 1, \qquad (2)$$

which is at 13 GeV/$c$ for deuterons, which is again above the maximum ZGS energy.

However, there is a serious $0\pm\nu_y$ intrinsic depolarizing resonance in deuteron acceleration. For protons, Eq. (1) indicates that this occurs at $E/m=0.45$, which is below the physical limit of 1. However, for deuterons the $0-\nu_y$ resonance occurs at 10.3 GeV/$c$ and must be passed. Because the zeroth-harmonic contributions are so strong this $0-\nu_y$ resonance is very strong. For protons it would be quite difficult to jump this resonance with the existing ZGS pulsed quadrupole magnets. Fortunately, the resonance strength is proportional to $(\frac{1}{2}g-1)$; thus the deuteron's small magnetic moment weakens the resonance by a factor of 12.5. By carefully tuning the pulsed quadrupoles, the ZGS staff was able to jump this $0-\nu_y$ resonance and obtain a beam of 12-GeV/$c$ deuterons with a neutron polarization of $P_B=(53\pm 3)\%$.

Measuring the polarization of these neutrons was also a new problem. A fast "uncalibrated" measurement of $P_B$ was made with the CERN polarimeter which measures the left-right scattering asymmetry, $A_m$, when the polarized beam scatters from a $CH_2$ target,

$$A_m=(L-R)/(L+R), \quad P_B=A_m/A. \qquad (3)$$

The effective analyzing power, $A$, of this fast polarimeter is obtained by calibration against our clean elastic polarimeter shown in Fig. 1, which detects only $p$-$p$ elastic scattering events from the liquid hydrogen target. We set this polarimeter to detect $p_\uparrow+p\to p+p$ events from the 6-GeV/$c$ polarized protons in the 12-GeV/$c$ polarized deuterons. Since the proton and neutron spins are correlated in a deuteron, measuring the proton polarization is equivalent to measuring the neutron polarization. Our polarimeter detected only events with a very small momentum transfer to the spectator neutron. This tight angular and momentum resolution rejected about 75% of the proton-proton elastic events. The polarimeter detected $P_\perp^2=1.0$ (GeV/$c$)$^2$ events, where the cross section is fairly large and the $p_\uparrow+p\to p+p$ analyzing power is $A=(14.4\pm 0.5)\%$.[4] With $10^9$ accelerated deuterons and about $3\times 10^8$ extracted deuterons, we were able to measure the polarization of the 6-GeV/$c$ neutrons with a precision of about 10% in 1 hour.

About 95% of the 12-GeV/$c$ polarized deuterons passed through the polarimeter's liquid $H_2$ target

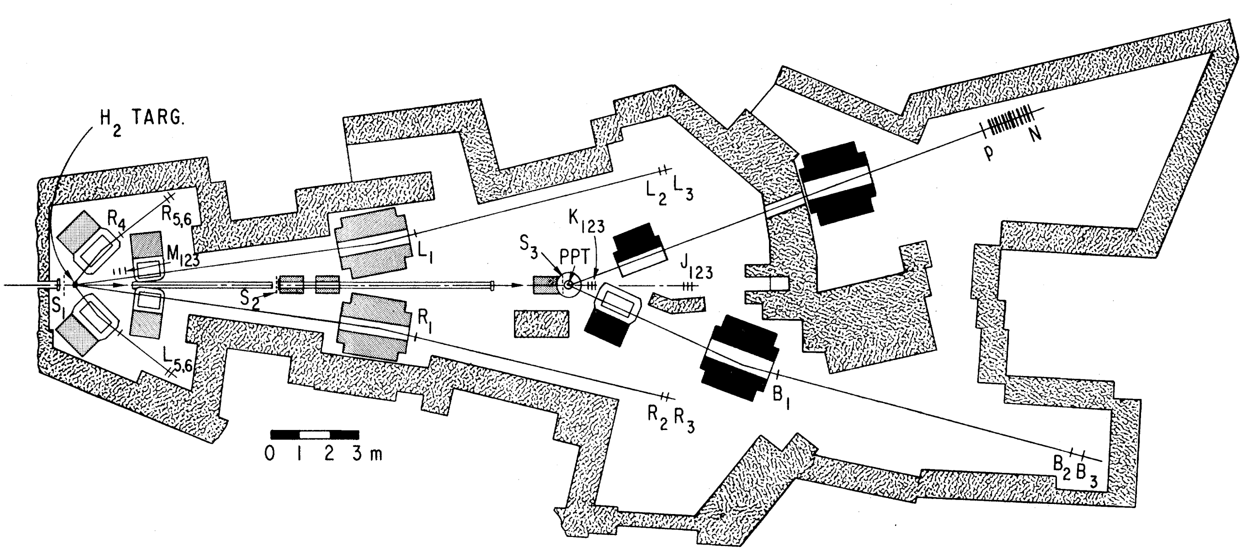


FIG. 1. Layout of the experiment. The polarized deuteron beam passes through the liquid $H_2$ target and the proton polarization is measured by the $L$-$R$ scattering asymmetry in the polarimeter. The deuterons then pass through the polarized proton target PPT and the elastic $n$-$p$ and $p$-$p$ events are detected by the recoil ($B_1\,B_2\,B_3$) spectrometer in coincidence with the neutron counter. The counters $M$, $J$, and $K$ monitor the beam intensity, while the chambers $S_1$, $S_2$, and $S_3$ monitor the beam position.

and were refocused onto our polarized proton target (PPT) by the quadrupole magnets shown in Fig. 1. The 6-GeV/$c$ polarized protons and polarized neutrons in the deuterons scattered from the polarized protons in this target. The polarized target[1,2,4] contained beads of $C_2H_6O_2$ doped with Cr V complexes, and used 70-GHz microwaves to transfer the polarization of the Cr electrons to the protons. The electrons were polarized by a 25-kG magnetic field at 0.5°K temperature. We monitored the proton polarization with a 107-MHz NMR system. The low neutron-beam intensity eliminated radiation-damage and beam-heating problems,[2] allowing us to maintain an average polarization of $P_T = (75 \pm 3)\%$ for the target protons.

We detected the recoil proton from $n$-$p$ or $p$-$p$ elastic scattering using the recoil spectrometer shown on the right in Fig. 1. This contained two bending magnets for momentum analysis and three scintillation counters ($B_1$, $B_2$, $B_3$) to count the number ($B_{123}$) of recoil protons. The 15×30-cm² $B_3$ counter was 20 m from the PPT and subtended a solid angle of $\Delta\Omega_{\text{c.m.}} = 3\times10^{-4}$ sr and had a momentum bite of $\Delta P/P = \pm 1\%$. We detected the forward-scattered neutron or proton using a "sandwich" neutron counter.[5] This contained six scintillation counters, each preceded by 6.3 cm of brass, which convert the uncharged neutrons into charged particles that trigger the adjacent scintillators. The signals from the six scintillators ($N_1$ to $N_6$) passed through discriminators into an OR circuit, $N_{123456}^{\text{OR}}$. The signal from a seventh scintillator ($p$), placed just in front of the neutron counter, vetoed charged particles. This $p$ signal was also the trigger for the forward-scattered proton in counting $p$-$p$ elastic events. Thus, we obtained the number of elastic $n$-$p$ and $p$-$p$ events by counting the electronic coincidences:

$$N(n\text{-}p) = \bar{p} \cdot N_{123456}^{\text{OR}} \cdot B_{123}, \qquad N(p\text{-}p) = p \cdot B_{123}. \tag{4}$$

The detection efficiency of the neutron counter was about 70% for the 5.5-GeV/$c$ neutrons.

The major difficulty in this $n$-$p$ experiment was the spread in angular and momentum resolution caused by the Fermi momentum of each nucleon in the deuteron, which is only about 2.5 times smaller than the carbon and oxygen Fermi momentum. An excessively tight resolution in the double-arm spectrometer would exclude most of the $n$-$p$ elastic scattering events. A very loose angular and momentum resolution would accept too many scattering events from the carbon and oxygen atoms in the PPT. We balanced these two difficulties in choosing the 23-cm×30-cm neutron counter; this gave a solid angle of $\Delta\Omega_{\text{c.m.}} = 2.5\times10^{-3}$ sr, which was 8 times larger than the $\Delta\Omega_{\text{c.m.}}$ of the defining recoil arm. The resulting resolution allowed us to detect about 30% of the true $n$-$p$ and $p$-$p$ elastic events, while keeping the background rate at about 20% of the event rate. We measured and subtracted this nonhydrogen background rate by taking data runs with the normal PPT beads replaced by Teflon beads which contain no hydrogen. We also continuously monitored the accidental coincidences using a standard "delayed"-coincidence circuit. This ~20% accidental background was subtracted from each data run.

We measured the elastic-event rates $N_{ij}(n\text{-}p)$ and $N_{ij}(p\text{-}p)$ in each of the four initial spin states

$$(i, j) \equiv (\text{beam, target}) = \uparrow\uparrow,\ \uparrow\downarrow,\ \downarrow\uparrow,\ \text{and}\ \downarrow\downarrow. \tag{5}$$

Both spins were measured transverse to the horizontal scattering plane and the neutron or proton forward scattered to the left. By correcting these $N_{ij}$ rates for the partial beam and target polarization, $P_B$ and $P_T$, we obtained the four pure initial-spin cross sections $(d\sigma/dt)_{ij}$ for $n$-$p$ and $p$-$p$ scattering. These are related to the spin-spin correlation parameter, $A_{nn}$, and the spin-orbit analyzing power, $A$, by the equations[6]

$$\begin{aligned} (d\sigma/dt)_{\uparrow\uparrow} &= \langle d\sigma/dt\rangle(1 + 2A + A_{nn}), \\ (d\sigma/dt)_{\downarrow\downarrow} &= \langle d\sigma/dt\rangle(1 - 2A + A_{nn}), \\ (d\sigma/dt)_{\uparrow\downarrow} &= (d\sigma/dt)_{\downarrow\uparrow} = \langle d\sigma/dt\rangle(1 - A_{nn}). \end{aligned} \tag{6}$$

Our new data are presented in Table I and in Fig. 2. The data on the $n$-$p$ analyzing power in Table I is in good agreement with two earlier measurements[7,8] using the ZGS polarized proton beam and liquid deuterium targets. This earlier

TABLE I. Analyzing power, $A$, and spin-spin correlation parameter, $A_{nn}$, for $n + p \to n + p$ and $p + p \to p + p$ at 6 GeV/$c$.

| Reaction | $P_\perp^2$ (GeV/$c$)$^2$ | $A$ (%) | $A_{nn}$ (%) |
|---|---|---|---|
| $n + p$ | 0.8 | $-6.5 \pm 2.2$ | $-17.0 \pm 4.5$ |
| | 1.0 | $-7.4 \pm 2.9$ | $-19.0 \pm 5.0$ |
| $p + p$ | 0.8 | $9.0 \pm 1.2$ | $6.4 \pm 2.6$ |
| | 1.0 | $16.4 \pm 1.3$ | $5.7 \pm 3.0$ |

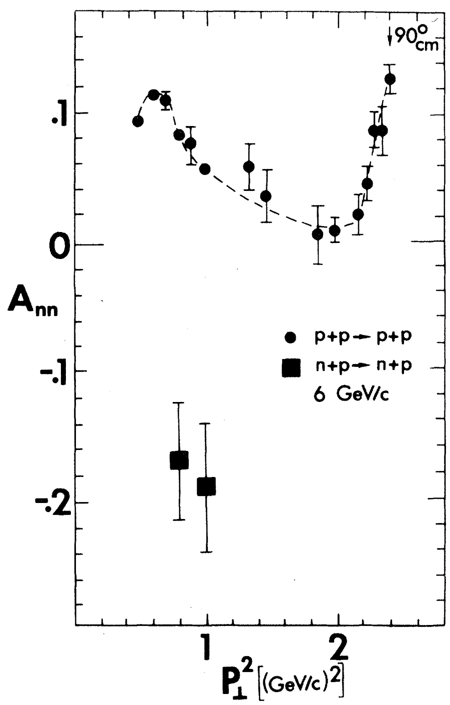


FIG. 2. The spin-spin correlation parameter, $A_{nn}$, for pure–initial-spin-state nucleon-nucleon elastic scattering at 6 GeV/$c$ is plotted against the square of the transverse momentum. The proton-proton and neutron-proton data are quite different.

technique is superior for measuring $A$ in $n$-$p$ scattering since it avoids the carbon and oxygen background in polarized targets. Our new measurements of $A$ and $A_{nn}$ in $p$-$p$ scattering also agree with the much more precise previous measurements[4,9] using a polarized proton beam and a polarized proton target. These measurements of $A(n\text{-}p)$, $A(p\text{-}p)$, and $A_{nn}(p\text{-}p)$ test the reliability of our technique for measuring $A_{nn}(n\text{-}p)$.

In Fig. 2 we have plotted our 6-GeV/$c$ $A_{nn}$ measurements for neutron-proton elastic scattering along with 6-GeV/$c$ proton-proton $A_{nn}$ measurements[4,9,10] for comparison. Notice that in the $P_\perp^2$ range available at 6 GeV/$c$, the spin-spin correlation parameter for $p$-$p$ scattering has some very interesting detailed structure. But it is quite small compared with the 60% effect[2] seen at the maximum $P_\perp^2$ available at 11.75 GeV/$c$. Also note that $A_{nn}$ is always positive for $p$-$p$ scattering, indicating that spin-parallel scattering is *always* more probable than spin-antiparallel scattering.[11]

The neutron-proton spin-spin effects seem to be quite different. Our data indicate that, near $P_\perp^2 = 1$ (GeV/$c$)$^2$, $A_{nn}$ for $n+p \rightarrow n+p$ is about twice as large as for $p+p \rightarrow p+p$. Moreover, $A_{nn}$ has the *opposite* sign; thus, the spin-antiparallel scattering is much more probable than the spin-parallel scattering.

This large negative $A_{nn}$ for $n$-$p$ elastic scattering is quite unexpected. No theoretical models predicted this effect, although a very recent constituent-interchange model[12] predicts $A_{nn} = -44\%$. This may support the suggestion that large spin effects are related to the composite nature of the nucleon.[12,13] An earlier Regge-model prediction[14] is inconsistent with our data. It seems somewhat surprising that $A_{nn}$ is so large at a $P_\perp^2$ of only 1 (GeV/$c$)$^2$.

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