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## Spin-Spin Interactions in High- $p_{\perp}^2$ Elastic $p$ - $p$ Scattering

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We measured  $d\sigma/dt$  for  $p + p \rightarrow p + p$  at 11.75 GeV/c using the zero-gradient synchrotron 70% polarized-proton beam and a 65% polarized-proton target. We obtained the spin-orbit asymmetry parameter  $A$  and the spin-spin correlation parameter  $C_{nn}$  out to  $P_{\perp}^2 = 4.2$  (GeV/c)<sup>2</sup>. We found that  $A$  drops smoothly towards zero, but that  $C_{nn}$  increases abruptly near  $P_{\perp}^2 = 3.6$  (GeV/c)<sup>2</sup>, where the  $\exp(-1.4P_{\perp}^2)$  component of elastic scattering becomes dominant. This suggests that large- $P_{\perp}^2$  "hard" elastic scattering may occur mostly when the two proton spins are parallel.

The role of spin in high-energy strong interactions was first successfully studied in polarized-target experiments at Berkeley,<sup>1</sup> CERN,<sup>2</sup> and Argonne.<sup>3</sup> The zero-gradient-synchrotron (ZGS) polarized-proton beam has allowed more precise measurements of the spin-orbit interaction and unique measurements of the spin-spin interaction in high-energy elastic scattering.<sup>4-9</sup> The recently improved ZGS intensity and polarization permitted extension of our  $p$ - $p$  elastic spin-spin measurements out to  $P_{\perp}^2 = 4.2$  (GeV/c)<sup>2</sup>. We found an unexpected and abrupt increase in  $C_{nn}$  starting at  $P_{\perp}^2 = 3.6$  (GeV/c)<sup>2</sup>.

The ZGS internal beam intensity reached  $4.2 \times 10^{10}$  per pulse during the polarized-proton run. The extracted beam intensity on our polarized target averaged about  $1.1 \times 10^{10}$ . By carefully correcting<sup>10</sup> for ten intrinsic depolarizing resonances and nineteen imperfection depolarizing resonances, the ZGS staff attained  $P_B = 70\%$  at 11.75 GeV/c for the first time. We measured  $P_B$  with a precision of about  $\pm 3\%$  using the high-energy polarimeter<sup>8</sup> shown in Fig. 1.

We scattered the polarized-proton beam from the Michigan-Argonne polarized-proton target PPT-V.<sup>6-8,11,12</sup> We annealed the PPT beads of

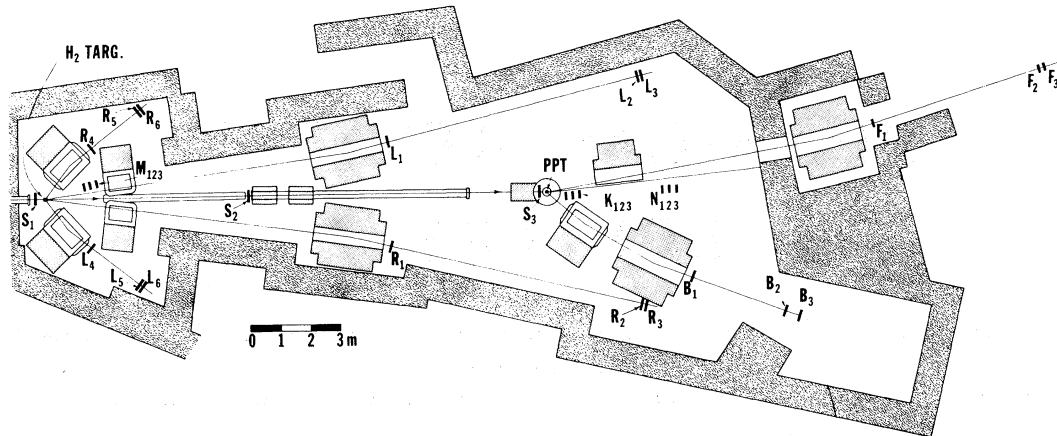


FIG. 1. Layout of the experiment. The polarized beam passes through the liquid- $H_2$  target and its polarization is measured by comparing the number of elastic events seen in the  $L$  and  $R$  spectrometers of the polarimeter. The beam then scatters in the polarized proton target (PPT) and the elastic events are counted by the  $F$  and  $B$  counters. The  $M$ ,  $N$ , and  $K$  counters are intensity monitors, while  $S_1$ ,  $S_2$ , and  $S_3$  monitor the beam position, size, and angle, respectively.

ethylene glycol doped with  $K_2Cr_2O_7$  every 8 h to remove the depolarization due to radiation damage. One of the two polarization states did not regain all its polarization during annealing and steadily deteriorated; thus we changed the target beads twice a week. We measured the target polarization,  $P_T$ , which averaged about 65%, with two independent NMR coils<sup>8</sup> with a precision of about  $\pm 3\%$ .

Events where the polarized-proton beam elastically scattered from the polarized-proton target were detected by the double-armed  $FB$  spectrometer which measured the angle and momentum of both outgoing protons using four magnets and the  $F_1F_2F_3$  and  $B_1B_2B_3$  scintillation counters. By varying the magnet currents we covered the range  $P_{\perp}^2 = 2.0-4.2$  ( $\text{GeV}/c$ )<sup>2</sup> without moving the detectors. The  $15 \times 20$ -cm  $F_3$  counter determined the center-of-mass solid angle of  $\sim 10^{-3}$  sr. The momentum bite was typically  $\Delta P/P = \pm 7\%$ . The  $B$  counters were overmatched to allow for beam size and divergence, magnet variations, and multiple Coulomb scattering. The accidentals were typically 1-3% and were continuously monitored and subtracted. Recoil magnet curves and Teflon bead runs measured the nonhydrogen event rate from the PPT, which was 3% at  $P_{\perp}^2 = 2.0$  ( $\text{GeV}/c$ )<sup>2</sup>, 16% at  $P_{\perp}^2 = 4.0$  ( $\text{GeV}/c$ )<sup>2</sup>, and 23% at  $P_{\perp}^2 = 4.2$  ( $\text{GeV}/c$ )<sup>2</sup>. This was subtracted at each  $P_{\perp}^2$ .

The relative beam intensity at the PPT,  $I_0$ , was monitored by the scintillation telescopes  $M$ ,  $N$ , and  $K$ .<sup>13</sup> The beam size at the 29-mm-diam by 41-mm-long PPT was about 10 mm full width at half-

maximum and the beam movement was less than 0.5 mm. More than 97% of the beam passed through the PPT. Possible systematic error due to variations in this number was reduced to below 1% by reversing the beam spin every pulse and the target spin every 8 h.

We obtained the four normalized elastic event rates

$$N_{ij} = E(ij)/I_0(ij) \quad (1)$$

by simultaneously measuring the number of elastic events  $E(ij)$  and the number of incident protons  $I_0(ij)$  in each of the four initial spin states ( $ij \equiv$  beam, target =  $\uparrow\uparrow$ ,  $\uparrow\downarrow$ ,  $\downarrow\uparrow$ , and  $\downarrow\downarrow$ ). The spin-spin correlation parameter  $C_{nn}$ , and the spin-orbit asymmetry parameter,  $A$ , obtained from the equations

$$C_{nn} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow} + N_{\downarrow\downarrow}}{P_B P_T \sum N_{ij}}, \quad (2)$$

$$A = \frac{2(N_{\uparrow\uparrow} - N_{\downarrow\downarrow})}{(P_B + P_T) \sum N_{ij}},$$

are listed in Table I and plotted in Fig. 2. We obtained the four pure two-spin cross sections,  $(d\sigma/dt)_{ij}$ , from the equations

$$\begin{aligned} (d\sigma/dt)_{\uparrow\uparrow} &= \langle d\sigma/dt \rangle [1 + 2A + C_{nn}], \\ (d\sigma/dt)_{\uparrow\downarrow} &= \langle d\sigma/dt \rangle [1 - 2A + C_{nn}], \\ (d\sigma/dt)_{\downarrow\uparrow} &= \langle d\sigma/dt \rangle [1 - C_{nn}]. \end{aligned} \quad (3)$$

The measured spin-average cross section  $\langle d\sigma/dt \rangle$  was obtained by renormalizing the large- $P_{\perp}^2$

TABLE I. Table of  $A$  and  $C_{nn}$  for each value of  $P_{\perp}^2$ . The quoted errors are statistical. There is an additional normalization uncertainty due to  $P_B$  and  $P_T$  which is approximately  $\pm 5\%$  of  $A$  and  $C_{nn}$ .

$P_{\perp}^2$ (GeV/c) <sup>2</sup>	$-t$ (GeV/c) <sup>2</sup>	$A$ (%)	$C_{nn}$ (%)
2.0	2.25	8.5 ± 0.8	8.7 ± 2.7
2.8	3.35	2.5 ± 0.7	6.7 ± 1.8
3.0	3.66	3.2 ± 1.0	9.3 ± 2.1
3.2	3.98	2.5 ± 0.9	2.7 ± 2.1
3.6	4.67	-0.2 ± 1.1	7.5 ± 2.4
4.0	5.47	2.8 ± 2.0	30.3 ± 4.5
4.2	5.92	2.9 ± 3.2	25.7 ± 7.2

12.1-GeV/c results of Allaby *et al.*<sup>14</sup> by a factor 1.21 to agree with their later small- $P_{\perp}^2$  12.0-GeV/c data.<sup>15</sup>

The left-right asymmetry parameter,  $A$ , is sometimes called the analyzing power and sometimes the polarization parameter,  $P$ . It parametrizes the spin-orbit interaction, for it measures that part of  $d\sigma/dt$  which depends on the spins being parallel or antiparallel to the orbital angular momentum. Similarly  $C_{nn}$  parametrizes the spin-spin interaction, for it measures the difference between the spin-parallel and spin-antiparallel

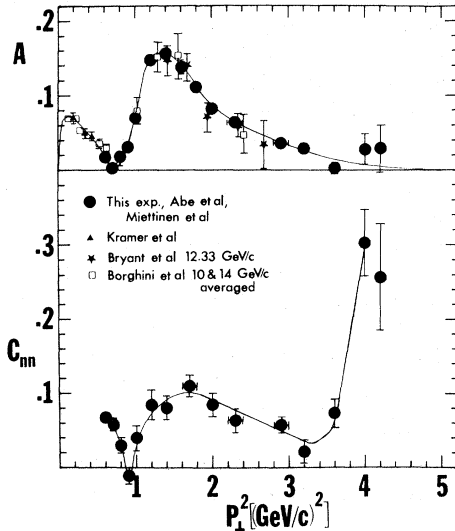


FIG. 2. The Wolfenstein parameters  $A$  and  $C_{nn}$  for  $p$ - $p$  elastic scattering at 11.75 GeV/c are plotted against  $P_{\perp}^2$ . To improve the statistical error at large  $P_{\perp}^2$ , we combined some adjacent  $P_{\perp}^2$  points in our present and earlier measurements (Refs. 8 and 9) and increased the bin sizes for some other experiments (Refs. 2, 16, and 17). The curves are hand-drawn lines to guide the eye.

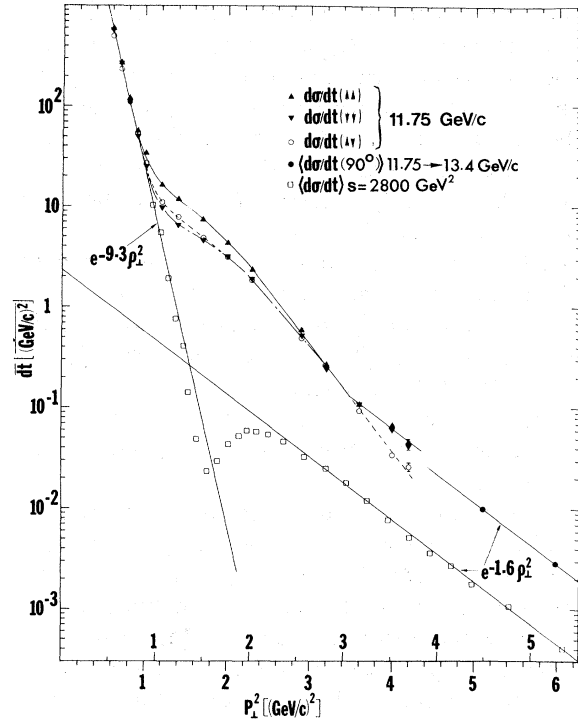


FIG. 3. The differential elastic proton-proton cross sections  $(d\sigma/dt)_{ij}$  for each pure initial spin state are plotted against  $P_{\perp}^2$  at 11.75 GeV/c. The initial spins ( $i, j$  = beam, target) are measured normal to the scattering plane and the forward proton scatters to the left. These pure-spin cross sections are normalized to measurements (Refs. 14 and 15) of  $\langle d\sigma/dt \rangle$  which have 8% to 15% errors. Spin-averaged  $90^\circ p + p \rightarrow p + p$  cross sections (Ref. 19) at the maximum ZGS energies are shown for comparison, along with  $s = 2800$  GeV<sup>2</sup> cross sections (Ref. 20) which are plotted against a universal variable  $\rho_{\perp}^2 = \beta^2 P_{\perp}^2 \sigma_{\text{tot}}(s)/38.3$  which removes much of the energy dependence of elastic scattering (Ref. 18). The  $P_{\perp}^2$  scale only applies to 11.75-GeV/c data while the  $\rho_{\perp}^2$  scale is valid at all energies.

cross sections.

Notice in Fig. 2 that  $A$  decreases smoothly in the large- $P_{\perp}^2$  region. Thus at high energy the spin-orbit interaction may not be very large in the small- $P_{\perp}^2$  diffraction peak or at very large  $P_{\perp}^2$  in spite of its structure in the medium- $P_{\perp}^2$  region.

The spin-spin correlation parameter,  $C_{nn}$ , has more dramatic structure. Notice the sharp zero at  $P_{\perp}^2 = 0.9$  (GeV/c)<sup>2</sup> and the broad maximum centered near  $P_{\perp}^2 = 1.7$  (GeV/c)<sup>2</sup>. Our new data indicate the  $C_{nn}$  rises rapidly at  $P_{\perp}^2 = 3.6$  (GeV/c)<sup>2</sup> and reaches a value of 0.30 at  $P_{\perp}^2 = 4.0$  (GeV/c)<sup>2</sup>.

The pure two-spin cross sections are plotted against  $P_{\perp}^2$  in Fig. 3, giving an overall picture

of spin effects in  $p$ - $p$  elastic scattering. The three different  $(d\sigma/dt)_{ij}$  are very close together in the forward diffraction peak; they then split apart just after the first break and join back together again further out in this medium- $P_{\perp}^2$  region. After the second break in  $\langle d\sigma/dt \rangle$  the abrupt change in  $C_m$  causes  $(d\sigma/dt)_{\uparrow\uparrow}$  to become twice as large as  $(d\sigma/dt)_{\uparrow\downarrow}$ .

The large  $C_m$  may be associated with the break in the sense of being caused by interference between the  $\exp(-3P_{\perp}^2)$  component at medium  $P_{\perp}^2$  and the  $\exp(-1.4P_{\perp}^2)$  component at high  $P_{\perp}^2$ .<sup>18</sup> Studying the  $P_{\perp}^2$  dependence of  $C_m$  might then give information about the relative phases and magnitudes of these two elastic components, in each spin state.

The large spin-spin interaction may instead be associated with the  $\exp(-1.4P_{\perp}^2)$  region itself. Then the ratio  $(d\sigma/dt)_{\uparrow\uparrow}/(d\sigma/dt)_{\uparrow\downarrow}$  might continue to grow with  $P_{\perp}^2$  or reach some constant value. Looking at the different slopes in Fig. 3 it is interesting to speculate on how much the parallel scattering dominates the antiparallel at higher  $P_{\perp}^2$ . The maximum  $P_{\perp}^2$  available at the ZGS polarized-proton beam is indicated by the 90° points.<sup>19</sup> It is also interesting to notice that  $(d\sigma/dt)_{\uparrow\uparrow}$  is pure triplet scattering while  $(d\sigma/dt)_{\uparrow\downarrow}$  is a mixture of singlet and triplet. Thus the triplet scattering dominates the singlet scattering by an even larger factor, if singlet and triplet scattering are well defined at these high energies.

Notice in Fig. 3 that the  $\exp(-1.4P_{\perp}^2)$  region at 11.75 GeV/c has essentially the same scaled<sup>18</sup> [ $\exp(-1.6\rho_{\perp}^2)$ ] slope as large- $P_{\perp}^2$  elastic scattering<sup>20</sup> at  $s = 2800$  (GeV/c)<sup>2</sup>. Thus by measuring the spin-spin forces in 11.75-GeV/c high- $P_{\perp}^2$   $p+p \rightarrow p+p$  we may already be directly probing the inner structure of the nucleon in a spin-sensitive way. This probing may indicate whether the inner structure can be most easily understood in terms of spinning geometrical clouds or in terms of pointlike constituent quarks with spin. Our data indicate that the spin-parallel interaction dominates the -antiparallel interaction by a factor of 2 at  $P_{\perp}^2 = 4.0$  (GeV/c)<sup>2</sup>, suggesting that the "hard"  $\exp(-1.6\rho_{\perp}^2)$  component is dominated

by spin-parallel scattering.

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