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High-$P_\perp^2$ p-p elastic scattering in pure initial spin states*

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We measured the cross section for proton-proton elastic scattering at 11.75 GeV/c using the Zero Gradient Synchrotron 52% polarized proton beam and a 60% polarized proton target. We measured $d\sigma/dt(ij)$ in the $\uparrow\uparrow$, $\downarrow\downarrow$, and $\uparrow\downarrow$ initial spin states perpendicular to the scattering plane in the range $P_\perp^2 = 2.0$–3.6 (GeV/c)^2. We found that the asymmetry parameter A decreases smoothly with increasing $P_\perp^2$ in this range, and that the spin-spin correlation parameter C_{nn} may have a minimum near $P_\perp^2 = 3$ (GeV/c)^2.

The spin dependence of strong interactions at high energy was first studied successfully in experiments using polarized proton targets at Berkely,[1] CERN,[2] and Argonne.[3] The Argonne Zero Gradient Synchrotron (ZGS) polarized proton beam has allowed new and more precise measurements of the elastic spin dependence.[4-8] The present experiment is the first accurate study of spin effects at $P_\perp^2$ above 2 (GeV/c)^2.

The polarized beam was accelerated to 11.75 GeV/c to match earlier measurements[8] at lower $P_\perp^2$. The accelerated beam intensity was as high as 3×10^{10} per 4.3 sec pulse. About 10% of the beam was extracted on a 6-GeV/c front porch and the rest was extracted at 11.75 GeV/c and shared. The extracted beam intensity on our polarized target was as high as 1.2×10^{10} and averaged about 7×10^9. There are many strong depolarizing resonances between 6 and 11.75 GeV/c, and it has not yet been possible to maintain the 70 to 75% beam polarization, P_B, normally available at 6 GeV/c. By carefully correcting[9] for 10 intrinsic resonances and 11 imperfection resonances the ZGS staff was able to reach P_B= 60% and the average polarization was 52% for the two-month run. The cause of the remaining depolarization is not yet completely understood. We measured P_B with a precision of about ±3% using the high-energy polarimeter described earlier[8] and shown in Fig. 1.

We scattered the polarized proton beam from the Michigan-Argonne PPT V polarized proton target,[10] which is a close copy of a CERN target[11] and is described in earlier papers.[6-8] We recently installed annealing heaters to quickly and reliably anneal the PPT beads of ethylene glycol doped with $K_2Cr_2O_7$. Annealing twice a day removed much much of the 20% depolarization due to radiation damage caused by about 10^{14} protons hitting the target. We found that one of the two polarization states did not regain all its polarization during annealing and its polarization steadily deteriorated. Therefore we changed the target beads about every five days. We measured the target polarization, P_T, with two independent NMR coils described earlier[8] with a precision of about ±3%. P_T was as high as 80% and averaged 60% for the run.

We detected events where the polarized proton beam elastically scattered from the polarized proton target using the double-armed FB spectrometer shown in Fig. 1. This spectrometer measured the angle and momentum of both the scattered proton and the recoil proton using four magnets and the six scintillation counters $F_1F_2F_3$ and $B_1B_2B_3$. By varying the magnet currents we covered the entire range $P_\perp^2$= 2.0–3.6 (GeV/c)^2 without moving the detectors. The c.m. solid angle was determined by the 15×20-cm F_3 counter placed about 18.4 m from the PPT, and was typically 10^{-3} sr. The momentum bite was typically $\Delta P/P = \pm 7\%$. The B counters were somewhat overmatched to allow for beam size and divergence, magnet variations, and multiple Coulomb scattering. The accidentals were less than $\frac{1}{2}$% and were continuously monitored and subtracted. Recoil magnet curves indicated that inelastic events and nonhydrogen events were less than 3%.

We monitored I_0, the beam intensity on the PPT, with the scintillation telescopes M, N, and K.[12] We monitored the size, position, and angle of the beam at the PPT using the segmented wire ion chambers shown in Fig. 1. The beam size at the 29-mm diameter–41-mm-long PPT was about 10 mm full width at half maximum (FWHM) and the beam movement was less than 0.5 mm. More than 97% of the beam passed through the PPT. Thus possible systematic error due to variations

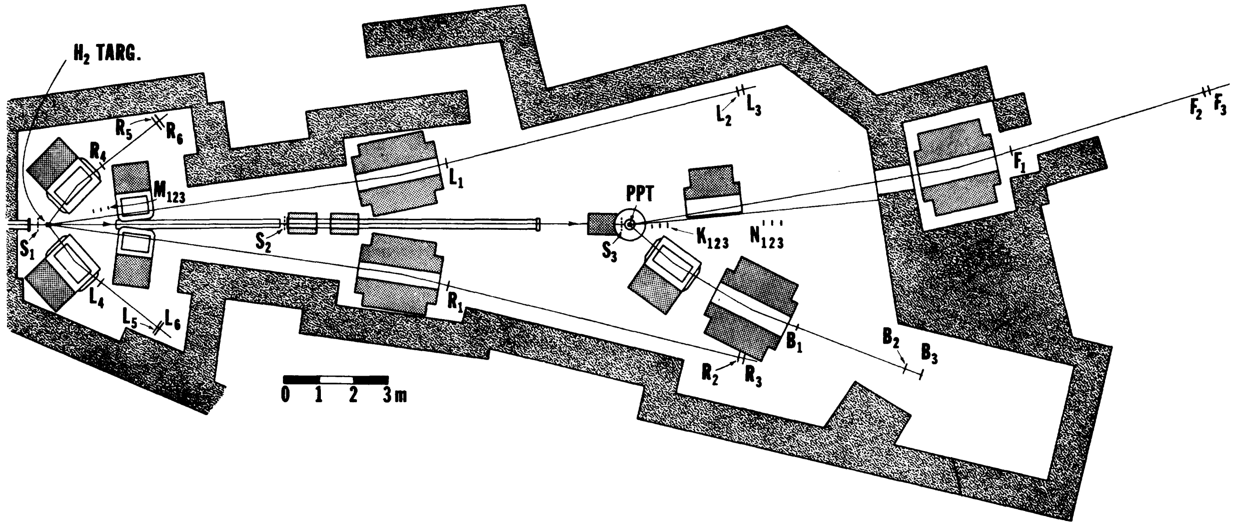

FIG. 1. Layout of the experiment. The polarized beam passes through the liquid H_2 target, and its polarization is measured by comparing the number of elastic events seen in the L and R spectrometers of the polarimeter. The beam then scatters in the polarized proton target (PPT) and the elastic events 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.

in this number were small. This error was further reduced to below 1% by reversing the beam spin every pulse and the target spin every six hours.

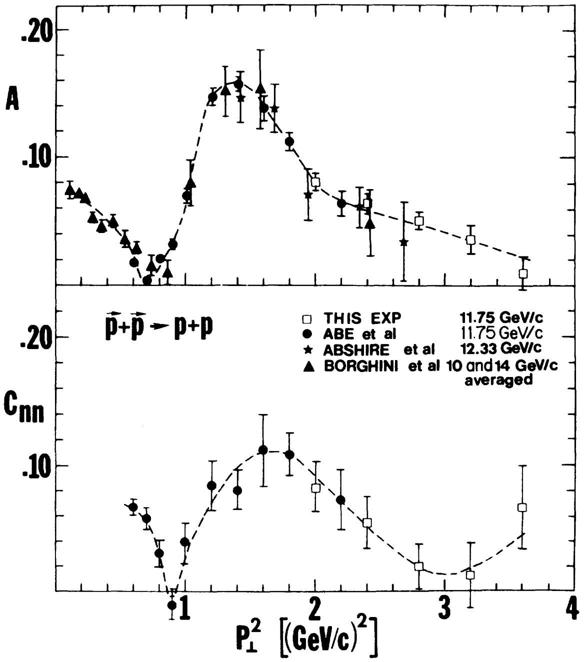

FIG. 2. The Wolfenstein parameters A and C_{nn} for p-p elastic scattering at 11.75 GeV/c are plotted against $P_\perp{}^2$. For some other experiments (Refs. 2 and 15) some bin sizes have been increased at large $P_\perp{}^2$ to improve the statistical error. The curves are handdrawn lines to guide the eye.

We obtained the four normalized elastic-event rates

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

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 ≡ beam, target = ↑↑, ↑↓, ↓↑, and ↓↓). The spin-spin correlation parameter C_{nn} was obtained from

$$C_{nn}=\frac{N_{\uparrow\uparrow}-N_{\uparrow\downarrow}-N_{\downarrow\uparrow}+N_{\downarrow\downarrow}}{P_B P_T \sum N_{ij}}\ . \tag{2}$$

The asymmetry parameter A was obtained by averaging over either the target or beam polarization

TABLE I. A and C_{nn} for each value of $P_\perp^2$. The quoted errors are statistical. There is an additional normalization uncertainty which is less than ±0.5%, coming from the uncertainty in P_B and P_T. The values of A_B and A_T, whose equality is a check of systematic errors, are also shown.

$P_\perp^2$ [(GeV/c)^2]	A (%)	C_{nn} (%)	A_B (%)	A_T (%)
2.0	8.1 ± 0.7	8.3 ± 2.0	7.5 ± 1.2	8.7 ± 0.9
2.4	6.4 ± 0.8	5.5 ± 2.1	5.2 ± 1.3	7.5 ± 0.9
2.8	5.1 ± 0.7	2.0 ± 1.8	4.7 ± 1.1	5.5 ± 0.9
3.2	3.6 ± 1.1	1.3 ± 2.6	5.7 ± 1.7	1.5 ± 1.5
3.6	1.0 ± 1.3	6.7 ± 3.3	−1.3 ± 2.1	3.3 ± 1.8

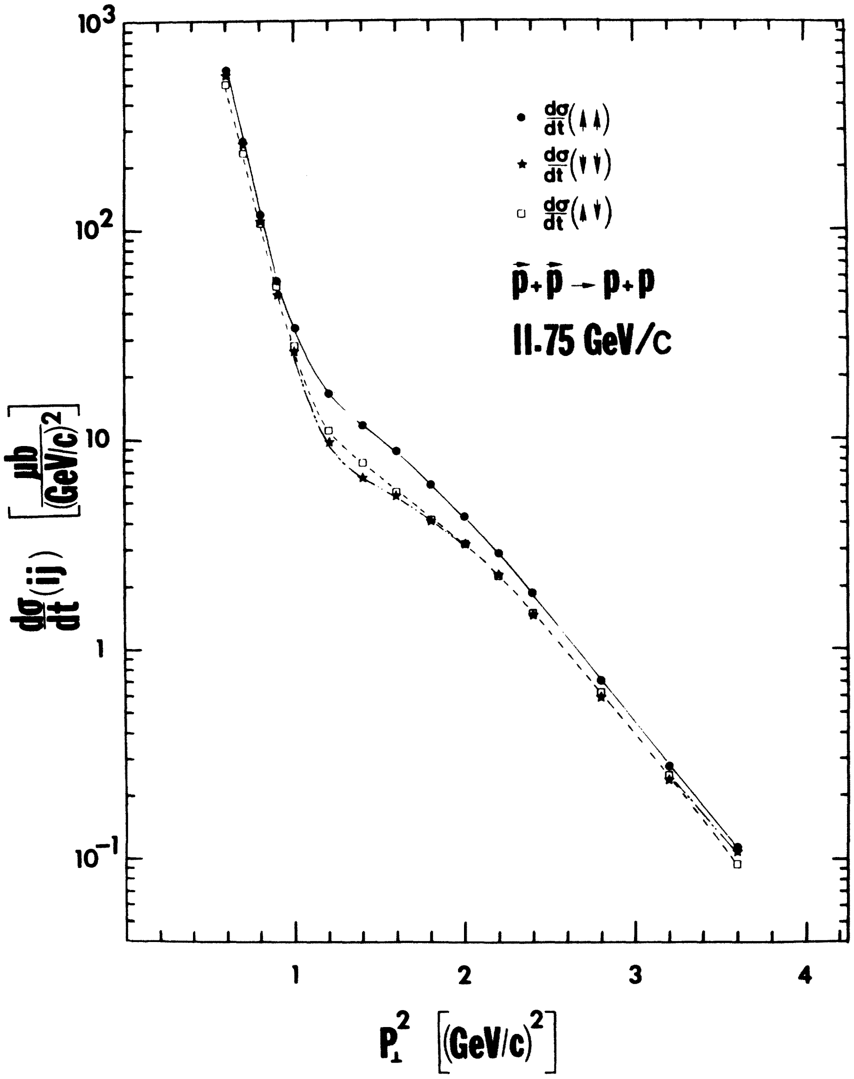

FIG. 3. The differential elastic proton-proton cross sections $d\sigma/dt(ij)$ for each pure initial spin state are plotted against $P_\perp^2$ at 11.75 GeV/c. The initial spins (i, j =beam, target) are measured normal to the scattering plane and the forward proton scatters to the left. These pure spin cross sections are normalized to measurements (Refs. 13 and 14) of $\langle d\sigma/dt\rangle$ which have 8 to 15% errors.

$$A_B=\frac{N_{\uparrow\uparrow}+N_{\uparrow\downarrow}-N_{\downarrow\uparrow}-N_{\downarrow\downarrow}}{P_B\sum N_{ij}},\qquad A_T=\frac{N_{\uparrow\uparrow}-N_{\uparrow\downarrow}+N_{\downarrow\uparrow}-N_{\downarrow\downarrow}}{P_T\sum N_{ij}}. \tag{3}$$

The equality of A_B and A_T, required by rotational invariance, gave the consistency check shown in Table I. We averaged A_B and A_T to obtain A. The values of A and C_{nn} are listed in Table I and plotted in Fig. 2. We obtained the four pure two-known-spin cross sections, $d\sigma/dt(ij)$, from the equations

$$\begin{aligned} d\sigma/dt(\uparrow\uparrow)&=\langle d\sigma/dt\rangle\,(1+2A+C_{nn})\,,\\ d\sigma/dt(\downarrow\downarrow)&=\langle d\sigma/dt\rangle\,(1-2A+C_{nn})\,,\\ d\sigma/dt(\uparrow\downarrow)&=d\sigma/dt(\downarrow\uparrow)\\ &=\langle d\sigma/dt\rangle\,(1-C_{nn})\,, \end{aligned} \tag{4}$$

where $\langle d\sigma/dt\rangle$ is the measured spin-average cross section. This is obtained by renormalizing the large-$P_\perp^2$ 12.1-GeV/c results of Allaby *et al.*[13] by a factor 1.21 to agree with their later small-$P_\perp^2$ 12.0-GeV/c data[14] which we used previously.[8]

Notice in Fig. 2 that the spin-orbit asymmetry parameter A has a narrow zero at $P_\perp^2=0.7$ (GeV/

$c)^2$ followed by a broad maximum centered near $P_\perp^2 = 1.4$ (GeV/c)^2. We now find that A decreases smoothly in the larger $P_\perp^2$ region. For several years supporters of an eikonal model[15,16] speculated that there might be a second zero near $P_\perp^2 = 2$ (GeV/c)^2. Our data appear to rule out this type of eikonal model.

The spin-spin correlation parameter C_{nn} has some interesting structure. Note the sharp zero at $P_\perp^2 = 0.9$ (GeV/c)^2 and the broad maximum centered near $P_\perp^2 = 1.7$ (GeV/c)^2. This is similar to the structure in A but occurs at slightly larger $P_\perp^2$. Our new data strongly suggest that C_{nn} falls toward zero near $P_\perp^2 = 3$ (GeV/c)^2 and may be rising again at $P_\perp^2 = 3.6$ (GeV/c)^2. A second zero in C_{nn} would give interesting information about the spin-spin forces at large $P_\perp^2$; however, our present statistical precision is too limited to be conclusive.

The pure two-spin differential elastic cross sections are plotted against $P_\perp^2$ in Fig. 3. This gives an overall picutre of the role of spin in p-p elastic scattering. In the forward diffraction peak the three different $d\sigma/dt(ij)$ are very close together showing that spin is not important in this highly diffractive region. However, the spin dependence becomes very large just after the break. At $P_\perp^2 = 1.4$ (GeV/c)^2, $d\sigma/dt(\uparrow\uparrow)$ is twice as large as $d\sigma/dt(\downarrow\downarrow)$. Further out in this large-$P_\perp^2$ region the three $d\sigma/dt(ij)$ come closer together again. Thus the spin dependence is largest just after the break where $\langle d\sigma/dt\rangle$ passes from the $\exp(-7.5P_\perp^2)$ diffraction peak to the $\exp(-2P_\perp^2)$ region.

There is another break in $\langle d\sigma/dt\rangle$ near $P_\perp^2 = 3.8$ (GeV/c)^2.[13,17] We are very eager to see if there is also a large spin dependence just after this second break. We particularly hope to see if the rise in C_{nn} at $P_\perp^2 = 3.6$ (GeV/c)^2 is real and is associated with the second break. The planned increase in the polarized-beam intensity this spring should allow even more accurate measurements of the spin dependence of strong interactions at large $P_\perp^2$. Perhaps these measurements will somehow tell us if the large-$P_\perp^2$ components of p-p elastic scattering are due to the proton having spinning cores[8,18] or due to the proton containing constituent quarks with spin.

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