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Spin Dependence of High-$P_\perp^2$ Elastic p-p Scattering

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We measured $d\sigma/dt$ for $p_\uparrow + p_\uparrow \to p+p$ from $P_\perp^2 = 4.50$ to 5.09 (GeV/c)^2 at 11.75 GeV/c. We used a 59%-polarized proton beam and a 71%-polarized proton target with both spins oriented perpendicular to the scattering plane. In these large-$P_\perp^2$ hard-scattering events, spin effects are very large and the ratio $(d\sigma/dt)_{\uparrow\uparrow}:(d\sigma/dt)_{\uparrow\downarrow}$ grows rapidly with increasing $P_\perp^2$, reaching a value of 4 at 90° (c.m.). Thus, hard elastic scattering, which is presumably due to the direct scattering of the protons' constituents, may only occur when the two incident protons' spins are parallel.

Last fall[1] our group reported measurements of proton-proton elastic-scattering cross sections at 11.75 GeV/c in pure initial-spin states out to $P_\perp^2 = 4.2$ (GeV/c)^2. We found that the spin-spin force has a very dramatic rise starting at $P_\perp^2 = 3.6$ (GeV/c)^2. This occurs just at the beginning of the large-$P_\perp^2$ hard-scattering component of p-p elastic scattering, which was seen most clearly by De Kerret *et al.* at $s = 2800$ GeV^2.[2] By $P_\perp^2 = 4.2$ (GeV/c)^2 the ratio $(d\sigma/dt)_{\uparrow\uparrow}:(d\sigma/dt)_{\uparrow\downarrow}$ had reached a value of almost 2. While it appeared most likely that this large spin-spin force was associated directly with the large-$P_\perp^2$, $\exp(-1.6P_\perp^2)$, hard-elastic-scattering component, it was also possible that it was associated with the interference between the hard-scattering component and the medium-$P_\perp^2$, $\exp(-3P_\perp^2)$ component. We have now extended these measurements to the maximum $P_\perp^2$ possible at 11.75 GeV/c.

We scattered an 11.75-GeV/c extracted polarized proton beam from our polarized proton target and measured the elastic event rate N_{ij} in each of the four initial-spin states.

$$i, j \equiv \text{beam, target} = \uparrow\uparrow,\ \uparrow\downarrow,\ \downarrow\uparrow,\ \text{and}\ \downarrow\downarrow. \qquad (1)$$

Both spins were measured transverse to the horizontal scattering plane and the forward proton scattered to the left. We also measured the beam polarization, P_B, and the target polarization, P_T, using a high-energy polarimeter and an NMR system. Both instruments have been described in earlier papers.[1,3] We corrected the four N_{ij} rates for the partial beam and target polarizations, and thus obtained the four pure initial-spin cross sections $(d\sigma/dt)_{ij}$. These are related to the spin-orbit analyzing power, A, and the spin-spin correlation parameter, A_{nn},[4] by the equations

$$(d\sigma/dt)_{\uparrow\uparrow} = \langle d\sigma/dt\rangle(1+2A+A_{nn}),$$
$$(d\sigma/dt)_{\downarrow\downarrow} = \langle d\sigma/dt\rangle(1-2A+A_{nn}), \qquad (2)$$
$$(d\sigma/dt)_{\uparrow\downarrow} = (d\sigma/dt)_{\downarrow\uparrow} = \langle d\sigma/dt\rangle(1-A_{nn}).$$

We normalized to the high-precision measurements of the spin-average $\langle d\sigma/dt\rangle$ of Albany *et al.*[5] and Akerlof *et al.*[6]

The general experimental technique was described previously, with the extracted polarized beam, the high-energy polarimeter, the polarized proton target (PPT), and the elastic spectrometer shown in Figs. 1 of Refs. 1 and 3. The only change was to improve the angular and momentum resolution by lengthening the recoil proton arm to about 18 m. This reduced the background event rate from the nonhydrogen nuclei in the PPT beads from our previous 23% at $P_\perp^2 = 4.2$ (GeV/c)^2 to 5% at $P_\perp^2 = 5.09$ (GeV/c)^2. This rate was measured and subtracted at each $P_\perp^2$ by running with hydrogen-free Teflon beads. The present run benefitted from the new record zero-gradient–synchrotron (ZGS) peak intensity of 5×10^{10} polarized protons per pulse. The average intensity on our PPT was just over 10^{10}/pulse and the PPT beads had to be annealed every 6 h and changed every 2 days to maintain the average target polarization of $71\pm4\%$. The average beam polarization was $59\pm3\%$ because of some difficulty with depolarizing resonance stability. In spite of these favorable conditions it required two full months of running to obtain about 900 events at each of three large-$P_\perp^2$, low-cross-section points.

Our new data are presented in Table I and in Fig. 1. From the table, one can clearly see that the spin-orbit analyzing power, A, is very close to zero for all three points. However the spin-spin correlation parameter, A_{nn},[4] has become strikingly large in this 90° (c.m.) region. This can be seen even more clearly in Fig. 1 where we plot, against $P_\perp^2$, the cross-section ratio for spin-parallel to spin-antiparallel scattering defined by

$$\frac{(d\sigma/dt)_{\uparrow\uparrow}}{(d\sigma/dt)_{\uparrow\downarrow}} \equiv \frac{(d\sigma/dt)_{\uparrow\uparrow}+(d\sigma/dt)_{\downarrow\downarrow}}{(d\sigma/dt)_{\uparrow\downarrow}+(d\sigma/dt)_{\downarrow\uparrow}} = \frac{1+A_{nn}}{1-A_{nn}}. \qquad (3)$$

Notice that on this log plot[7] the spin effects that previously seemed very large,[1,8] now appear small in comparison with the behavior near 90° (c.m.).

In fact, this new data make it appear very likely that the large spin-spin interaction is directly associated with the $\exp(-1.6P_\perp^2)$ region itself. The ratio $(d\sigma/dt)_{\uparrow\uparrow}:(d\sigma/dt)_{\uparrow\downarrow}$ already reaches a value of 4 at the maximum $P_\perp^2$ presently available at the ZGS. As can be seen from the dashed and solid lines our present errors are too large to determine if the ratio has reached an asymptotic value of about 4 or is still growing. We hope to get more data on this question sometime in the

TABLE I. Values of A and A_{nn} for each value of $P_\perp^2$. The errors include statistical and systematic errors added in quadrature.

$P_\perp^2$ (GeV$^2/c^2$)	$-t$ (GeV$^2/c^2$)	A (%)	A_{nn} (%)	$\frac{(d\sigma/dt)_{\uparrow\uparrow}}{(d\sigma/dt)_{\uparrow\downarrow}}$
4.50	6.71	3 ± 3	55 ± 8	$3.5^{+0.9}_{-0.7}$
4.80	7.75	2 ± 4	60 ± 8	$4.0^{+1.2}_{-0.8}$
5.09	10.18	0 ± 4	59 ± 10	$3.9^{+1.5}_{-1.0}$

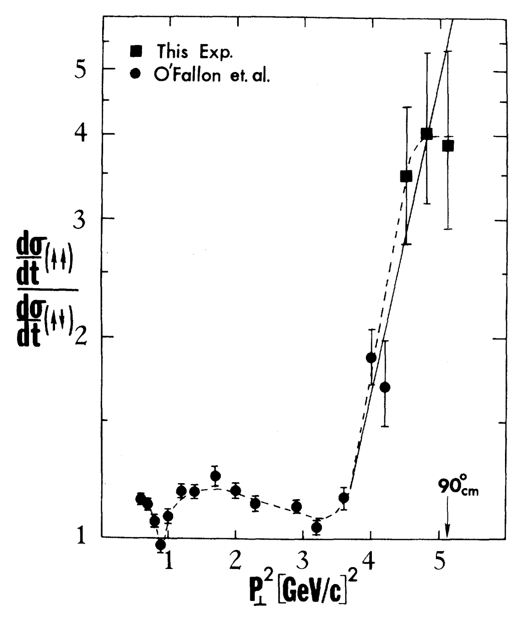

FIG. 1. Plot of the ratio of the differential elastic cross sections in pure initial-spin states for $p+p\to p+p$ at $P_{lab}=11.75$ GeV/c. The spin-parallel cross section increases dramatically relative to the spin-antiparallel cross section at the onset of the hard-scattering component at $P_\perp^2=3.6$ (GeV/c)^2. The curves are only to guide the eye.

future. In any case it seems both remarkable and intriguing that the largest spin-spin effect ever observed in high-energy physics occurs at the maximum polarized proton energy and $P_\perp^2$ presently available in the world.

In Figure 2 the spin-parallel (↑↑) and spin-antiparallel (↑↓) cross sections are plotted against the scaled $P_\perp^2$ variable,[9] $\rho_\perp^2$, giving an overall picture of spin-spin effects in *p-p* elastic scattering. From $\rho_\perp^2 = 0$ to 3 $(\mathrm{GeV}/c)^2$ the two cross sections are quite equal except for a small spreading just near the break at the end of the diffraction peak. The familiar $\exp(-1.6\rho_\perp^2)$ hard-scattering component, seen by DeKerret *et al.*,[2] then suddenly appears at $\rho_\perp^2 \sim 3$ $(\mathrm{GeV}/c)^2$, but apparently *only* in the spin-parallel cross section $(d\sigma/dt)_{\uparrow\uparrow}$. Our data are consistent with there being *no* hard-scattering break at all when the protons' spins are antiparallel.

This large spin-spin effect in high-$P_\perp^2$ elastic *p-p* scattering may be due to the spin dependence of the direct scattering of the constituents of the proton. We do not know the exact nature of these consitutents but the slope of 1.6 $(\mathrm{GeV}/c)^{-2}$ corresponds to a size of about $\frac{1}{3}$ fm, which may be a measure of the constituents' size. The large spin-spin force would then indicate that these $\frac{1}{3}$-fm constituents rarely scatter unless their spins are parallel.

This new fact may help us to understand the nature and the number of the proton's spinning constituents. More generally, large-$P_\perp^2$ spin effects may give strong constraints on any theory that associates large-$P_\perp^2$ scattering experiments with the fundamental constituents of the proton. The large-$P_\perp^2$ spin dependence may even suggest which of these theories is useful and which should be abandoned.[9]

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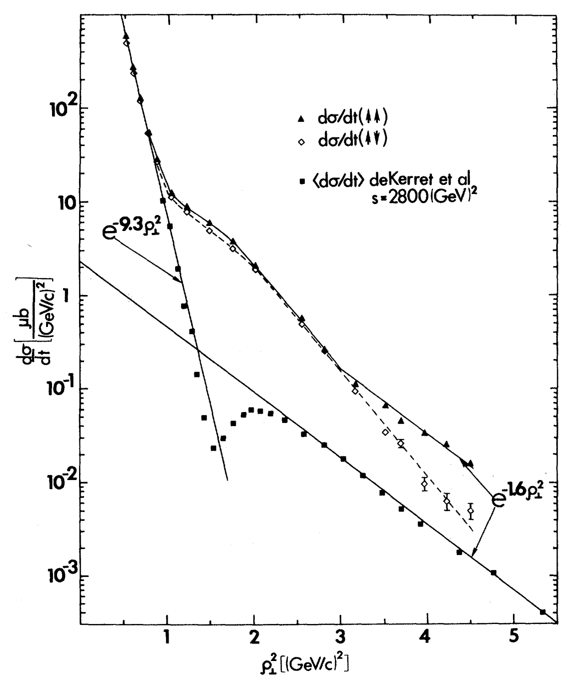

FIG. 2. The 11.75-GeV/c spin-dependent proton-proton elastic cross sections are plotted against $\rho_\perp^2 = \beta^2 P_\perp^2 \sigma_{\mathrm{tot}}(s)/38.3$, the $P_\perp^2$ scaled according to the Lorentz-contracted geometric model (Ref. 9). $(d\sigma/dt)_{\uparrow\uparrow}$ denotes scattering with the incident protons' spins parallel while $(d\sigma/dt)_{\uparrow\downarrow}$ denotes scattering with the spins antiparallel. Both spins are measured transverse to the scattering plane. Spin-averaged data from Ref. 2 are plotted for comparison, showing that the slope of the hard-scattering component is the same at 11.75 GeV/c and $s = 2800$ GeV^2 when plotted against $\rho_\perp^2$.

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[1]J. R. O'Fallon *et al.*, Phys. Rev. Lett. 39, 733 (1977).

[2]H. DeKerret *et al.*, Phys. Lett. 62B, 363 (1976), and 68B, 374 (1977).

[3]A. Lin *et al.*, Phys. Lett. 74B, 273 (1978).

[4]The quantity previously called C_{nn} is now called A_{nn} according to the Ann Arbor Convention for Spin Parameters, in *Higher Energy Polarized Proton Beams*, AIP Conference Proceedings No. 42, edited by A. D. Krisch and A. J. Salthouse, 1977 (American Institute of Physics, New York, 1978).

[5]J. V. Allaby *et al.*, Nucl. Phys. B52, 316 (1973), and CERN Report No. 68-7/580, 1968 (unpublished).

[6]C. W. Akerlof *et al.*, Phys. Rev. 159, 1138 (1967).

[7]We have plotted the cross-section ratio rather than A_{nn} because we feel that this displays these large spin effects in a more direct way.

[8]K. Abe *et al.*, Phys. Lett. 63B, 239 (1976); H. E. Miettinen *et al.*, Phys. Rev. D 16, 549 (1977).

[9]A. D. Kirsch, Phys. Rev. Lett. 19, 1149 (1967), and Phys. Lett. 44B, 71 (1973), and in Lectures in 1978 Orbis Scientia Proceedings, Coral Gables (to be published); P. H. Hansen and A. D. Kirsch, Phys. Rev. D 15, 3287 (1977).