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Energy dependence of spin-spin effects in p-p elastic scattering at $90°_{c.m.}$

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The energy dependence of the spin-parallel and spin-antiparallel cross sections for $p_{\uparrow}+p_{\uparrow}\to p+p$ at $90°_{c.m.}$ was measured for beam momenta between 6 and 12.75 GeV/c. The ratio $(d\sigma/dt)_{\text{parallel}}:(d\sigma/dt)_{\text{antiparallel}}$ at 90° is about 1.2 up to 8 GeV/c and then increases rapidly to a value of almost 4 near 11 GeV/c. Our data indicate that this ratio may depend only on the variable $P_{\perp}^2$, and suggests that the ratio may reach a limiting value of about 4 for large $P_{\perp}^2$.

The unique polarized proton beam at the now-closed Argonne Zero Gradient Synchrotron (ZGS) allowed measurements of spin-spin forces at high energy. For some years our group has been studying the spin-spin correlation parameter A_{nn} in high-$P_{\perp}^2$ proton-proton elastic scattering using the polarized beam and a polarized proton target. In a fixed-energy experiment[1] at 11.75 GeV/c we found a sharp and unexpected increase in this spin-spin effect at the threshold for large-$P_{\perp}^2$ hard scattering. However, it was not clear whether this huge dramatic effect was a large-$P_{\perp}^2$ effect or a $90°_{c.m.}$ effect. We have measured the $90°_{c.m.}$ energy dependence of A_{nn} from 6 GeV/c up to the 12.75-GeV/c ZGS maximum. We found conclusive evidence that the dramatic increase is a high-$P_{\perp}^2$ hard-scattering effect and a suggestion that the size of the effect may reach a limiting value.

Because of particle identity the p-p analyzing power A vanishes at $90°_{c.m.}$. This makes $90°_{c.m.}$ a particularly simple and appropriate point to study the dynamics of strong interactions at high $P_{\perp}^2$. In an earlier experiment[2] we measured A_{nn} for p-p elastic scattering at $90°_{c.m.}$ between 1.75 and 5.5 GeV/c with both spins oriented perpendicular to the horizontal scattering plane. In the 6-to-12.75-GeV/c experiment we chose the beam momenta to avoid extraction near the known depolarizing resonances,[3] and the ZGS staff maximized the beam polarization P_B at each momentum using a fast uncalibrated polarimeter. The hydrogen target polarimeter[4,5] shown in Fig. 1 was used for an absolute measurement of P_B. This measured elastic p-p scattering, near $P_{\perp}^2=1.4$ (GeV/c)^2, to the left and to the right of the beam direction. The polarization was calculated from

$$P_B=\frac{1}{A}\frac{L-R}{L+R}. \tag{1}$$

The values of A given in Table I were obtained by interpolating between measurements at nearby energies.[4-7]

Immediately downstream from the polarimeter was our polarized proton target (PPT)[5,8] containing ethylene glycol beads doped with $K_2Cr_2O_7$. Two NMR coils inside the target measured the target polarization P_T to a precision of about 3%. For unirradiated beads, P_T was about 80% and it averaged about 65% during the runs.

The beam intensity on the target reached 3×10^{10} protons/pulse and averaged over 1×10^{10} protons/pulse. The radiation damage and local beam heating caused by this high intensity reduced P_T.[9] The target beads were annealed every eight hours and changed every few days to minimize the radiation-damage problem. To make the reduction in P_T more uniform over the 6.6-cm² target area, the beam spot size was increased during the experiment from 2.4 cm × 2.4 cm to 3.4 cm × 3.4 cm full

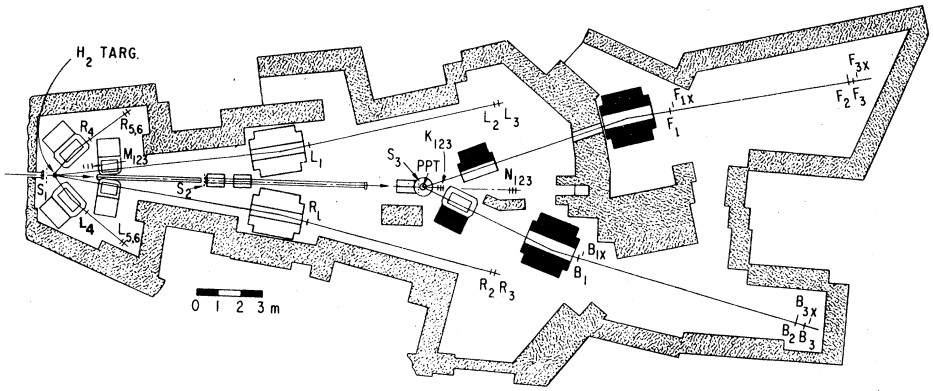

FIG. 1. Layout of the experiment. The polarized beam passes through the liquid-H_2 target and its polarization is measured by comparing the number of elastic p-p events seen in the L and R spectrometers of the polarimeter. The beam then scatters in the polarized proton target (PPT) and the elastic events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

width at half maximum. The data obtained with the smaller spot size at the highest intensity deviates more than 1 standard deviation from the remaining data. Therefore, the highest intensity/cm^2 runs at the 11.75-GeV/c $90°_{c.m.}$ point were removed from the data sample. All the remaining runs gave statistically consistent results.[10]

Elastically scattered protons were counted by the double-arm spectrometer[1,2,4,5] shown in Fig. 1. This consisted of two bending magnets and two scintillation-counter hodoscopes in each arm. The spectrometer subtended a $\Delta\Omega_{c.m.}$ of about 2 msr. The contamination of inelastic and quasielastic events from the heavy nuclei in the PPT beads was measured by taking background data with the PPT beads replaced by hydrogen-free Teflon beads. We found an experimental background rate of $(7\pm1)\%$ for the smaller spot size and $(14\pm2)\%$ for the larger spot size.

We measured the proton-proton elastic-scattering event rate in each spin state by flipping the beam spin each pulse and the target spin every few hours. We corrected these event rates for the partial polarization of the beam and target (P_B and P_T), and thus obtained the relative values of the cross section in each of the four initial pure spin states: $\sigma_{\uparrow\uparrow}$, $\sigma_{\uparrow\downarrow}$, $\sigma_{\downarrow\uparrow}$, and $\sigma_{\downarrow\downarrow}$. The spin-spin correlation parameter A_{nn} and the ratio of the spin-parallel to spin-antiparallel cross sections are obtained from these relative cross sections using

$$\frac{(d\sigma/dt)_{\text{parallel}}}{(d\sigma/dt)_{\text{antiparallel}}}=\frac{\sigma_{\uparrow\uparrow}+\sigma_{\downarrow\downarrow}}{\sigma_{\uparrow\downarrow}+\sigma_{\downarrow\uparrow}}=\frac{1+A_{nn}}{1-A_{nn}}. \quad (2)$$

Similarly, the analyzing power A is given by

$$A=\frac{\sigma_{\uparrow\uparrow}-\sigma_{\downarrow\downarrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\downarrow\downarrow}+\sigma_{\uparrow\downarrow}+\sigma_{\downarrow\uparrow}}. \quad (3)$$

Our experimental results are listed in Table II. Notice that, for all $90°_{c.m.}$ points, A is equal to zero within experimental errors, as required by particle identity. We also remeasured the $70°_{c.m.}$ point at 11.75 GeV/c and found good agreement with our earlier measurement.[1]

The $90°_{c.m.}$ energy dependence of A_{nn} is shown in Fig. 2. We previously found[2,11] that A_{nn} falls steeply near 3 GeV/c from a value of about 60% to about 10%. We now see a rapid increase near 9 GeV/c, up to a value of about 60%. This curve seems to us quite striking, since it clearly displayes the existence of several distinct regions. This spin behavior strongly suggests dramatic changes in the fundamental $90°_{c.m.}$ scattering mechanism as one goes to higher energy and thus further into the hard-scattering region.

The fixed-energy angular dependence of $(d\sigma/dt)_{\text{parallel}}:(d\sigma/dt)_{\text{antiparallel}}$ at 11.75 GeV/c is plotted in Fig. 3 together with the $90°_{c.m.}$ energy depen-

TABLE I. The analyzing power for $p+p\to p+p$ near $P_\perp^2=1.4$ (GeV/c)^2 for our incident momenta. Except for the measured points at 6.0 and 11.75 GeV/c, the quoted errors contain an estimated uncertainty for the interpolation.

P_{lab} (GeV/c)	$P_\perp^2$ [(GeV/c)^2]	A
6.0	1.0	0.144 ± 0.003
7.0	1.2	0.177 ± 0.009
8.0	1.4	0.216 ± 0.020
9.0	1.4	0.173 ± 0.009
10.2	1.4	0.168 ± 0.009
11.1	1.4	0.163 ± 0.009
11.75	1.4	0.157 ± 0.006
12.75	1.5	0.145 ± 0.008

TABLE II. Measurements of the analyzing power and the spin-spin correlation parameter for $p+p \rightarrow p+p$ at $90°_{\text{c.m.}}$. The quoted errors are the combined statistical errors and systematic errors due to the uncertainty in the background and the P_B and P_T measurements.

P_{lab} (GeV/c)	$\theta_{\text{c.m.}}$	$P_\perp^2$ [(GeV/c)^2]		A (%)	A_{nn} (%)
6.0	90°	2.41		0 ± 1	12 ± 1
7.0	90°	2.87		2 ± 2	7 ± 2
8.0	90°	3.34		-2 ± 2	9 ± 3
9.0	90°	3.81		-1 ± 1	26 ± 2
10.2	90°	4.37		1 ± 2	47 ± 4
11.1	90°	4.79		-1 ± 2	52 ± 5
11.75	90°	5.09	New	-2 ± 2	57 ± 5
			1978	-1 ± 7	59 ± 10
			Average	-2 ± 2	58 ± 4
12.75	90°	5.56		-3 ± 5	59 ± 9
11.75	70°	4.50	New	5 ± 2	48 ± 7
			1978	3 ± 3	54 ± 7
			Average	4 ± 2	51 ± 5

dence of this ratio. Bot sets of data are plotted against $P_\perp^2 = P_{\text{c.m.}}^2 \sin^2\theta_{\text{c.m.}}$. The similarity suggests that pure spin cross sections may depend only on $P_\perp^2$ in the hard-scattering region. The data show directly that the dramatic increase in spin forces is due to large-$P_\perp^2$ hard-scattering effects as opposed to $90°_{\text{c.m.}}$ particle-identity effects.

At the highest values of $P_\perp^2$ the ratio seems to flatten off somewhat and may be approaching a limiting value of about 4 corresponding to an A_{nn} of 60%. If this value of 4 continues beyond the 12.75 GeV/c available at the ZGS then this limit may reflect some fundamental aspect of hard scattering which is not yet understood.

This experiment is in a kinematical region which is difficult for most current theories of hadronic scattering. Some Regge models[12,13] can fit the spin parameters at small $P_\perp^2$ but they fail above 1 (GeV/c)^2. The constituent models, which were somewhat successful in describing large-$P_\perp^2$ unpolarized hadron collisions,[14] have also tried to predict the spin parameters, but they are apparently valid only at *very* large energies and $P_\perp^2$, where no data are available.

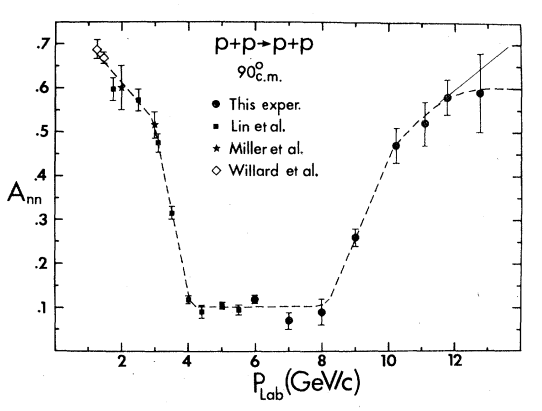

FIG. 2. Plot of the spin-spin correlation parameter A_{nn} for $p+p \rightarrow p+p$ at $90°_{\text{c.m.}}$ as a function of incident beam momentum. The dashed and solid lines are hand-drawn possible fits.

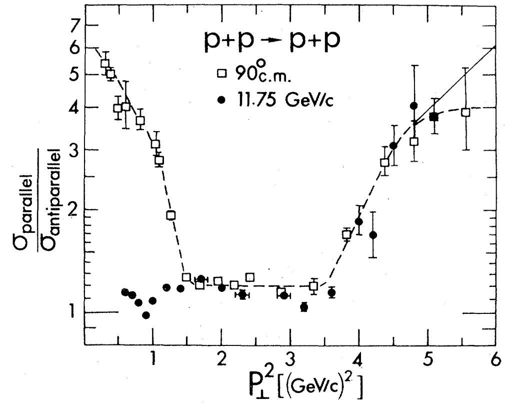

FIG. 3. Plot of the ratio of the spin-parallel to spin-antiparallel differential cross sections, as a function of $P_\perp^2$, for p-p elastic scattering. The squares are the fixed-angle data at $90°_{\text{c.m.}}$, with the incident energy varied. The circles are data (Refs. 5, 11) with the momentum held fixed at 11.75 GeV/c while the scattering angle is varied. The dashed and solid lines are hand-drawn possible fits to the $90°_{\text{c.m.}}$ data.

The simplest quark-interchange model[15,16] predicts a constant cross-section ratio of 2, and additional mechanisms such as triple-scattering diagrams[16] and instanton effects[15] have been proposed to enhance the spin effects. While both these models fit the large-$P_\perp^2$ angular distribution reasonably well, the basic quark-interchange model has difficulty with the energy dependence. Recent models, considering the first-order quantum-chromodynamic scattering of two fast valence quarks[17] and the inherent spin effects due to quark confinement itself,[18] can obtain a spin ratio of 3 to 4 by making certain detailed assumptions.

While none of these models can yet explain simply both the energy dependence and the angular distribution of these spin effects, they demonstrate the variety of ideas[19] attempting to deal with these huge unexpected spin-spin forces in hadronic scattering at large $P_\perp^2$.

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