Large-$P_\perp^2$ Spin Effects in $p+p \rightarrow p+p$

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The analyzing power A in 28-GeV/c proton-proton elastic scattering was measured with a polarized proton target and a high-intensity unpolarized proton beam at the Brookhaven National Laboratory alternating-gradient synchrotron. The $P_\perp^2$ range of 2.85 to 5.95 (GeV/c)^2 was covered with good precision. A small dip of about -3.5% was found near $P_\perp^2 = 3.5$ (GeV/c)^2 where a 24-GeV/c CERN experiment had reported a deep dip of about -16% with large errors. In the previously unexplored large-$P_\perp^2$ region near 6 (GeV/c)^2 these new large-error points suggest that A may be rising.

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Polarized proton beams and targets allow the study of spin effects in high-energy strong interactions. Since the start of the first polarized proton beam at the zero-gradient synchrotron (ZGS) in 1973, many interesting and unexpected spin effects have been discovered, such as the large spin-spin forces in high-$P_\perp^2$ proton-proton elastic scattering.[1] We recently[2] reported alternating-gradient synchrotron (AGS) measurements of the analyzing power A in $p+p \rightarrow p+p$ at 28 GeV/c in the $P_\perp^2$ range of 0.5 to 2.8 (GeV/c)^2. Such one-spin experiments give information about the spin-orbit interaction by measuring the analyzing power, which is sometimes called the polarization. We recently scattered a considerably higher-intensity unpolarized proton beam from our improved polarized proton target and measured the p-p elastic-scattering cross section in the previously unexplored region out to $P_\perp^2 = 6$ (GeV/c)^2. We detected the elastic-scattering events using a double-arm spectrometer consisting of magnets and scintillation-counter hodoscopes.

The experiment was run at the Brookhaven National Laboratory's alternating-gradient synchrotron (AGS) with use of a primary extracted beam of about 7×10^{10} protons/pulse at 28 GeV/c. We installed fast steering magnets in the D beam line to compensate for small variations in the AGS beam momentum, which could cause significant variations in the beam position at our polarized proton target (PPT). The steering magnets were servo-coupled to a split-plate ion chamber near the PPT to reduce the horizontal beam motion. The beam position and the 10×12-mm^2 full width at half maximum (FWHM) ($H \times V$) spot size at our PPT were monitored continuously by three upstream segmented wire ion chambers (SWICs), and the beam position was kept centered to within ± 0.5 mm. The relative beam intensity was measured by five independent monitors.[2] Elastic scattering events were detected by the double-arm FB spectrometer shown in Fig. 1 of Ref. 2. The angles and momenta of both outgoing protons were measured with use of six magnets and the forward (F) and backward (B) four-channel scintillation counter hodoscopes, with each channel defining a center-of-mass solid angle of about 6×10^{-4} sr. We collimated the magnet apertures with lead to reduce the single-arm rates and thus the accidental rate which was typically less than 10%. The data at each $P_\perp^2$ point were corrected with use of the measured accidental rate.

The incident proton beam was scattered from the Michigan polarized proton target[3] (PPT) consisting of a ^{3}He evaporation cryostat inside a ^{4}He evaporation cryostat, a 25-kG dipole magnet, a 70-GHz microwave system, and a 107-MHz NMR system. The target beads were contained in a cylindrical copper cavity 29 mm in diameter by 40 mm along the beam direction. The ^{3}He cryostat maintained a 0.5-K temperature in the cavity which was placed in the highly uniform 25-kG vertical magnetic field.[2] We actually used a 40%-60% mixture of ^{3}He-^{4}He in the ^{3}He cryostat. The ^{3}He supercools the ^{4}He to 0.5 K where ^{4}He is a superfluid with high heat-transfer capacity. This ^{3}He-^{4}He mixture allowed operation at a beam intensity of 7×10^{10}/pulse with a polarization loss of less than 10% due to local beam heating. We believe that this new mode of PPT operation appears quite promising for use with very high-intensity beams.

To eliminate the radiation damage problem due to the high beam intensity, we used chemically undoped crystalline ammonia (NH_3) beads, which become polarizable when irradiated. The beads were irradiated with 70-MeV electrons from the linac at the National Synchrotron Light Source. The radiation produces electron centers which allow the microwaves to polarize the protons.[4,5] The radiation damage with these NH_3 beads was quite slow and was completely annealed away by warming to 95 K. Moreover, the average polarization steadily increased as we collected data and the beam protons created new centers. The target polarization, P_T, reached 55% after irradiation with about 10^{17} particles/cm^2. We continuously monitored P_T with a $\pm$ 3% uncertainty using two independent NMR coils of different radii.

We covered the $P_\perp^2$ range of 2.85 to 5.95 (GeV/c)^2 by varying the magnet currents without moving the detectors or magnets. At each $P_\perp^2$ setting, we varied the coincidence logic timing and the magnet currents about the calculated values to assure a clean elastic signal at the correct $P_\perp^2$ value. The background rate for nonhydrogen events was measured by replacing the normal PPT beads with Teflon beads which contain no hydrogen. The measured nonhydrogen background correction factor was respectively 1.13 ± 0.01, 1.18 ± 0.02, 1.19 ± 0.03, and 1.21 ± 0.06 at $P_\perp^2$ values of 3.8, 4.2, 4.7, and 5.2 (GeV/c)^2. We corrected all data as indicated in Table I, using a linear fit for the $P_\perp^2$ dependence of this background.

We scattered the unpolarized proton beam from the polarized proton target in each transverse spin state ($i=\uparrow$ or $\downarrow$) and obtained the normalized event rates $N(i)$ by measuring

$$N(\uparrow)=\text{Events}(\uparrow)/I(\uparrow),\quad N(\downarrow)=\text{Events}(\downarrow)/I(\downarrow), \tag{1}$$

where Events(i) is the number of FB events corrected for accidentals and nonhydrogen background and $I(i)$ is the beam intensity obtained by averaging the monitors, M, N, K, SEC, and Ion (see Ref. 2). When all five monitors did not agree within 1% we eliminated the monitor or monitors with the largest disagreement. We used the F and B single-arm rates to check the monitor consistency further. The analyzing power was obtained from our measured values of $N(i)$ with use of the equation

$$A=-\frac{1}{P_T}\,\frac{N(\uparrow)-N(\downarrow)}{N(\uparrow)+N(\downarrow)}\,. \tag{2}$$

We use the Basel convention; thus the minus sign occurs because our forward proton scatters to the right.

The results are tabulated in Table I along with our estimated uncertainty, which includes both

TABLE I. The analyzing power A in 28-GeV/c proton-proton elastic scattering at various values of $P_\perp^2$. Estimates of the systematic errors have been added in quadrature with statistical errors. The background correction factor was fitted to be $0.98\pm0.044\,P_\perp^2$ from the measured Teflon points at $P_\perp^2=3.8$, 4.2, 4.7, and 5.2 (GeV/c)^2.

$P_\perp^2$ (GeV/c)^2	A, uncorrected	Background correction factor	A
2.85	0.04 ± 1.17	1.10 ± 0.03	0.0 ± 1.3
3.00	-0.14 ± 1.48	1.11 ± 0.03	-0.2 ± 1.7
3.30	-3.07 ± 1.23	1.13 ± 0.03	-3.5 ± 1.4
3.80	2.04 ± 1.35	1.15 ± 0.03	2.4 ± 1.6
4.20	1.44 ± 2.03	1.17 ± 0.03	1.7 ± 2.4
4.95	5.33 ± 2.60	1.20 ± 0.04	6.4 ± 3.2
5.95	10.58 ± 7.76	1.24 ± 0.05	13.1 ± 9.6

statistical and systematic errors. The results are plotted in Fig. 1 along with the 24-GeV/c CERN data[6] and our earlier data.[2] There is generally good agreement between the experiments within errors, except that our earlier point at $P_\perp^2 = 2.8$ (GeV/c)^2 seems somewhat high. Upon reexamination we found two possible problems with the earlier point. The first recoil magnet was set slightly low probably giving a true $P_\perp^2$ value near 2.7 (GeV/c)^2. Thus the rapid variation of A could cause some of the difference. There could also be some systematic error due to the beam position stability since the servomagnet system was not yet installed. A statistical fluctuation could easily have caused much of the difference, and so we plan to remeasure the point.

One notable feature of our data is the dip near $P_\perp^2 = 3.5$ (GeV/c)^2 where A drops to about -3.5%. This dip is much less deep in our data than in the CERN data; however, the CERN data has quite large errors. It is very interesting that this dip occurs near the sharp slope change in the differential cross section, which is at exactly the same $P_\perp^2 = 3.5$ (GeV/c)^2 where the dramatic increase in spin-spin effects was observed[1] at the ZGS.

Note that beyond $P_\perp^2 = 3.5$ (GeV/c)^2 it appears

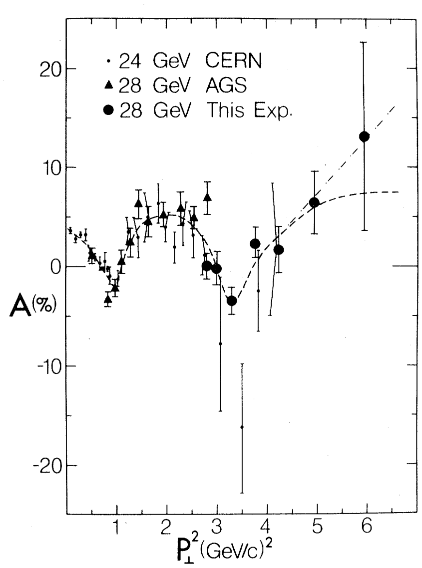

FIG. 1. The analyzing power A as a function of $P_\perp^2$ for pp elastic scattering at 28 GeV/c. The error bars for the present experiment include both statistical and systematic errors. The 24-GeV/c CERN data (Ref. 6) and our earlier AGS data (Ref. 2) are also shown. The curves are hand-drawn lines demonstrating flat and rising behavior at large $P_\perp^2$.

that A may be increasing. The errors are large and better statistics are clearly needed near $P_\perp^2 = 6$ (GeV/c)^2; nevertheless, the data suggest interesting and quite unexpected behavior in this previously unexplored large-$P_\perp^2$ region. The 12-GeV ZGS data[1] on A showed little deviation from zero in the $P_\perp^2$ range of 3.5 to 5 (GeV/c)^2. However, at 12 GeV, the $P_\perp^2 = 5$ (GeV/c)^2 point occurs at 90° (c.m.) where A must be zero from symmetry. Most theoretical models predict that A should be zero at large $P_\perp^2$. Our data are not in good agreement with zero beyond $P_\perp^2 = 3$ (GeV/c)^2. Thus, this first look at spin effects at large $P_\perp^2$ suggests the possibility of unexpected spin-orbit forces in hard scattering.

The striking structure observed in various high-$P_\perp^2$ spin experiments cannot be explained by present theories of strong interactions, such as QCD. The rapid increase in spin-spin effects discovered at the ZGS occurs exactly at the start of the large-$P_\perp^2$ hard scattering region. The dip in A near $P_\perp^2 = 3.5$ (GeV/c)^2 occurs at the same start of the hard-scattering region. The occurrence of both spin effects at the exact position of the break in $d\sigma/dt$ suggests that these spin effects may be associated with the onset of some hard-scattering mechanism. We hope soon to study in more detail the possible rise in A near $P_\perp^2 = 6$ (GeV/c)^2 and to search for further spin effects in the totally unexplored hard-scattering region beyond $P_\perp^2 = 6$ (GeV/c)^2.

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