High-Precision Measurement of the Analyzing Power in Large-$P_\perp^2$ Spin-Polarized 24-GeV/c Proton-Proton Elastic Scattering

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We measured the analyzing power A out to $P_\perp^2 = 7.1$ (GeV/c)^2 with high precision by scattering a 24-GeV/c unpolarized proton beam from the new University of Michigan polarized proton target; the target's 1-W cooling power allowed a beam intensity of more than 2×10^{11} protons per pulse. This high beam intensity together with the unexpectedly high average target polarization of about 85% allowed unusually accurate measurements of A at large $P_\perp^2$. These precise data confirmed that the one-spin parameter A is nonzero and indeed quite large at high $P_\perp^2$; most theoretical models predict that A should go to zero.

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Polarized beams and polarized targets allow the study of spin effects in high-energy collisions. Using the 12-GeV/c Argonne Zero Gradient Synchrotron polarized proton beam, a large and unexpected spin-spin correlation parameter A_{nn} was found in high-$P_\perp^2$ proton-proton elastic scattering.[1-3] Our group[4] later found evidence for an equally unexpected nonzero analyzing power A in $p+p_\uparrow \rightarrow p+p$ at 28 GeV/c at high $P_\perp^2$. There has been a strong theoretical belief[5-23] that all spin effects should be small at high energy and large $P_\perp^2$ and that in particular A should then be zero. Because of their small cross section, high-$P_\perp^2$ experiments are quite difficult; the fairly large errors in our 28-GeV/c experiment caused concern about the reliability of the nonzero-A result.[4] Our new polarized proton target has a 1-W cooling power, which allows about 4 times more beam intensity than was previously possible; moreover, the target has an unexpectedly high polarization.[24] These two factors along with an improved spectrometer increased the precision of our new measurements by a factor of about 3. The resulting precise data on A in 24-GeV/c p-p elastic scattering confirm the existence of a large one-spin effect at high $P_\perp^2$.

The experiment was performed at the Brookhaven Alternating Gradient Synchrotron (AGS) using an extracted 24-GeV/c unpolarized proton beam of about 2×10^{11} protons per pulse every 2.4 sec. We scattered these protons from the new University of Michigan polarized proton target (PPT), as shown in Fig. 1. The beam position and the 13-mm-diam FWHM beam size at our PPT were monitored continuously by four segmented wire ion chambers S_1, S_2, S_4, and S_5. Upstream steering magnets were servo-coupled to split segmented wire ion chambers to reduce the horizontal beam motion; the average beam position was kept centered to within about ±0.1 mm. The relative beam intensity was measured using an ion chamber (Ion), a secondary-emission chamber (SEC), and three scintillation-counter telescopes N, K, and B, which counted the secondary particles produced by the beam.

The new polarized proton target used the dynamic nuclear polarization technique in a magnetic field (B) of 5.0 T while operating at a temperature (T) of 1.0 K produced by a ^{4}He evaporation refrigerator. For the target material we used ammonia (NH_3) with radiation-induced[24] unpaired electrons. The 2-mm-diam ammonia beads had a hydrogen proton density of about 0.1 g/cm^3 and were contained in a cylindrical cavity 20 mm in diameter by 36 mm long. At our temperature of 1 K, the 5-T field polarized the radiation-induced unpaired electrons in the ammonia beads. Microwaves of about 140 GHz were used to transfer the electron polarization to the hydrogen protons in the ammonia. The proton polarization was reversed by changing the microwave frequency by about 0.38 GHz. We continuously measured the target polarization P_T using a 213-MHz NMR system.

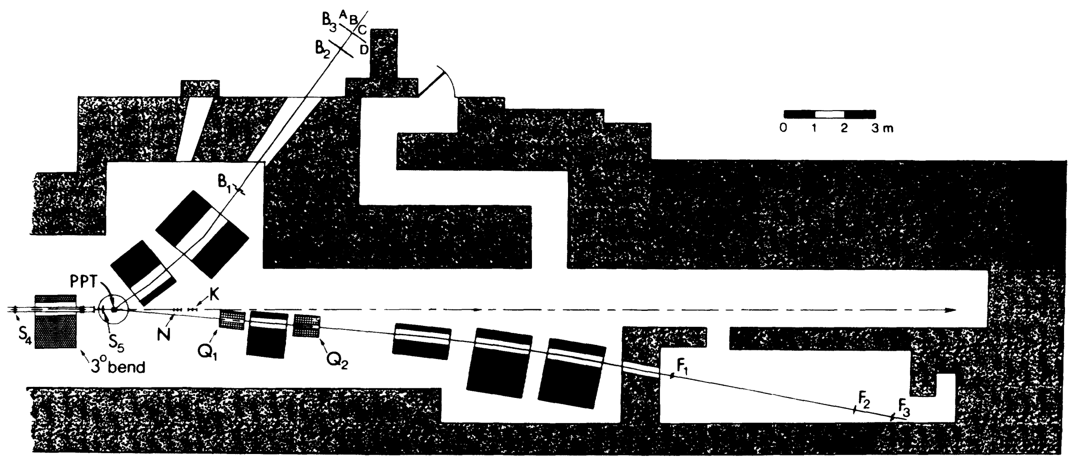

FIG. 1. Diagram of the experiment. A new magnet bent the beam to the left by about 3°. The unpolarized proton beam then scattered in the vertically polarized proton target (PPT); the elastic events were detected by the spectrometer which contained magnets for momentum analysis, the Q_1 and Q_2 quadrupoles for focusing, and the F and B scintillation-counter hodoscopes. The N and K counters were intensity monitors, while the S_4 and S_5 segmented wire ion chambers monitored the beam's position, size, and angle.

The system was calibrated in special runs with both the microwaves and the beam turned off; the resulting thermal equilibrium proton polarization was given by

$$P_{\mathrm{TE}} = \tanh(\mu_p B/kT)\,, \tag{1}$$

where μ_p is the proton's magnetic moment and k is the Boltzmann constant. There was a $\pm 3\%$ relative uncertainty in P_{TE}, and thus in P_T, caused mostly by the temperature uncertainty. Other uncertainties in P_T were below 1%.

For yet unexplained reasons ammonia has a very high proton polarization[24] at 5 T and 1 K. The polarization typically reached 96% after each annealing, which was done about twice each day to remove the radiation damage caused by our high average beam intensity of about 10^{11} protons/sec. The average target polarization was typically about 85% as shown in Table I.

Elastic-scattering events were detected by the double-arm FB spectrometer shown in Fig. 1. The angles and momenta of both outgoing protons were measured using six dipole magnets and the forward and backward eight-channel scintillation-counter hodoscopes. A p-p elastic-scattering event was defined by a sixfold FB coincidence between the appropriate channels of the $F = F_1F_2F_3$ arm and the $B = B_1B_2B_3$ arm. The four horizontally split $(25\times 35$ cm$)$ $(h\times v)$ B_3 counters and the four horizontally split $(7.5\times 14$ cm$)$ F_3 counters along with the vertically split F_2 and B_2 counters defined eight channels; each channel had a center-of-mass solid angle of about 3×10^{-4} sr. The other counters were overmatched to allow for beam size, beam divergence, magnet variations, and multiple Coulomb scattering. The momentum bite $\Delta P/P$ was about $\pm 5\%$. Accidental coincidences were continuously monitored by delayed FB coincidence circuits. Data at each $P_\perp^2$ point were corrected using the measured accidental rate of less than 1%.

One significant change from our earlier experiments[4]

TABLE I. Data on A at $P_{\mathrm{lab}} = 24$ GeV/c.

$P_\perp^2$ [(GeV/c)^2]	P_T (%)	Events	Target-spin reversals	Teflon correction factor	$[\chi^2/(N-1)]^{1/2}$	A (%)
3.2	84.5	68929	42	1.06	0.92	0.7 ± 0.5
3.4	84.5	60709	42	1.10	1.08	-0.5 ± 0.5
3.6	84.5	43931	42	1.12	1.11	1.8 ± 0.7
3.8	84.5	20267	42	1.15	1.11	1.0 ± 1.0
4.3	83.4	18521	22	1.11	1.12	3.8 ± 1.0
4.7	83.4	8860	22	1.12	0.89	3.4 ± 1.5
5.3	88.3	13043	48	1.21	0.80	6.6 ± 1.3
5.7	88.3	7879	48	1.22	0.95	11.1 ± 1.7
6.7	81.5	4906	64	1.59	0.84	16.2 ± 2.7
7.1	81.5	2768	64	1.58	0.91	20.4 ± 3.9

was the addition of a magnet which bent the beam to the left by about 3° just before the beam hit the target; this 3° bend allowed our spectrometer to detect larger-$P_\perp^2$ events which have a larger forward angle and a smaller backward (recoil) angle. Another significant change was the addition of two focusing quadrupole magnets Q_1 and Q_2 which increased the forward-arm solid-angle acceptance by up to a factor of 2. This was especially important at large $P_\perp^2$ where the event rate was small and the kinematics made the forward arm defining. We also improved our phototube bases to allow operation near a very intense beam; our total luminosity on the NH_3 beads was more than $10^{35}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

The unpolarized proton beam was scattered from the vertically polarized proton target and we detected elastic events in the horizontal plane for each transverse target spin state ($j=\uparrow$ or $\downarrow$). We then obtained the normalized event rates $R(j)$ by measuring the quantity

$$R(j)=N(j)/I(j)\,. \tag{2}$$

For each spin state, $N(j)$ was the number of FB elastic events corrected for accidentals and $I(j)$ was the relative beam intensity obtained by averaging the monitors N, K, B, SEC, and Ion which agreed to better than 1%. The analyzing power A was obtained from our measured $R(j)$ using the equation

$$A=-\frac{1}{P_T}\left[\frac{R(\uparrow)-R(\downarrow)}{R(\uparrow)+R(\downarrow)}\right], \tag{3}$$

where P_T is the target polarizations. The minus sign comes from the Ann Arbor convention because our forward protons scattered to the right.

At each spectrometer magnet setting, we simultaneously measured four different $P_\perp^2$ points which each covered a $P_\perp^2$ range of about 0.2 $(\mathrm{GeV}/c)^2$; at the larger $P_\perp^2$ values we combined two adjacent $P_\perp^2$ points to improve the statistical error. To assure that we had a clean elastic signal at the correct $P_\perp^2$ value, we varied the coincidence logic timing and the magnet currents about the calculated values. We also checked that the elastic peak was approximately diagonal in the matrix logic discussed below. The background rate for nonhydrogen and inelastic events was experimentally estimated by special runs with the normal NH_3 beads in the PPT replaced by Teflon (CF_2) beads which contain no hydrogen. We then multiplied each NH_3 measurement of A by the appropriate measured background correction factor listed in Table I.

We analyzed the data using a 100-MHz scaler system and independently using a new matrix logic system, which also recorded off-diagonal elements in the forward-backward hodoscope matrix. We then obtained three independent values of A for each $P_\perp^2$ point by using three different methods: scalers, diagonal-matrix logic, and extended-matrix logic. The scalers and diagonal-matrix methods recorded almost identical data. The extended-matrix technique also included those adjacent elements whose signal to Teflon background ratio was at least 50% of the diagonal element's ratio; this gave about 20% more NH_3 events, but about 30% more Teflon events. We then averaged the three corrected values of A and their errors (σ) to obtain our final values. The average spread in the A values obtained using the three methods was about 0.25σ.

Our results for A in 24-GeV/c proton-proton elastic scattering are listed in Table I for various $P_\perp^2$ values along with our estimated total errors. The 3% relative error in the target polarization and the typically 1% relative error in the measured background correction factor gave almost negligible errors in A; we added these systematic errors in quadrature to the statistical errors. For each $P_\perp^2$ value we also list the target polarization, the number of scaler events, the number of target-spin reversals, and the average measured Teflon background-correction factor. We also list the quantity $[\chi^2/(N-1)]^{1/2}$; we estimated the systematic error for each $P_\perp^2$ point by summing the χ^2 for every matched data pair associated with the $2N$ target-spin reversals. Note that $[\chi^2/(N-1)]^{1/2}$ is always quite close to 1; this indicates that most other systematic errors were small.

Our new 24-GeV/c data on the one-spin analyzing power A are shown in Fig. 2 along with our earlier 28-

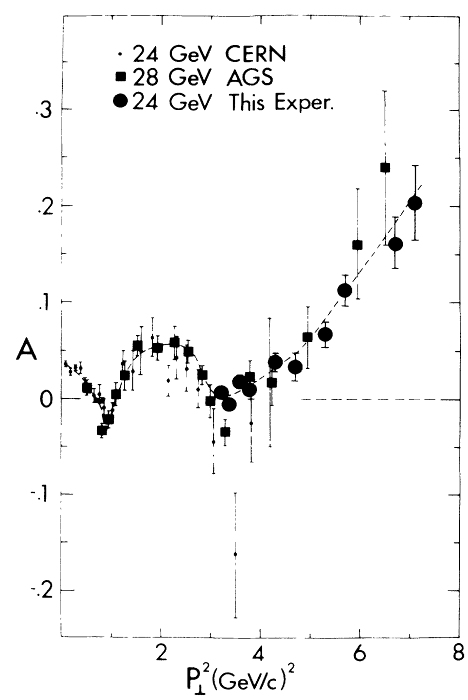

FIG. 2. The analyzing power A as a function of momentum transfer squared $P_\perp^2$ for spin-polarized proton-proton elastic scattering at 24 GeV/c. The error bars include both the statistical and systematic errors. Other data at 28 (Ref. 4) and 24 GeV/c (Ref. 25) are also shown. The dashed curve is a hand-drawn curve to guide the eye.

GeV/c data[4] and the 24-GeV/c data from CERN.[25] The new data have errors which are about 3 times smaller at high $P_\perp^2$. The dominant feature of our precise new 24-GeV/c data is that *A clearly increases and becomes nonzero at high $P_\perp^2$*. This confirms our earlier result[4] which indicated that the one-spin asymmetry A in $p+p_\uparrow \to p+p$ at 28 GeV/c appears to be large and nonzero at high $P_\perp^2$.

While many theoretical models[5-23] have been suggested to explain the large spin effects found in strong interactions, models based on perturbative QCD imply that the analyzing power should be zero[16] at high energy and large $P_\perp^2$. Our new high-precision data make it difficult to assume that this disagreement between theory and experiment will disappear because the nonzero A is a statistical fluctuation. Perhaps one should now try to gain some new theoretical understanding of strong interactions that is consistent with this and other large and unexpected spin effects.

We plan to extend these measurements of A to higher energy, first at 400 GeV and then at 3 TeV, at the new UNK facility now being constructed in the U.S.S.R. This NEPTUN-A experiment should determine whether these yet unexplained nonzero spin effects will disappear, persist, or perhaps grow in the TeV region.

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