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Measurement of $p_\uparrow + p_\uparrow \rightarrow p + p$ with a 16.5-GeV/c polarized proton beam

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Using the new Brookhaven Alternating Gradient Synchrotron polarized proton beam and our polarized proton target, we measured the spin-spin correlation parameter A_{nn} in 16.5-GeV/c proton-proton elastic scattering. We found an A_{nn} of $(6.1 \pm 3.0)\%$ at $P_\perp^2 = 2.2$ (GeV/c)^2. We also measured the analyzing power A in two independent ways, providing a good test of possible experimental errors. Comparing our new data with 12-GeV Argonne Zero Gradient Synchrotron data shows no evidence for strong energy dependence in A_{nn} in this medium-$P_\perp^2$ region.

With polarized proton beams and targets one can study spin effects in high-energy strong interactions. Since the start of the first polarized proton beam at the Argonne Zero Gradient Synchrotron (ZGS) in 1973, many interesting and unexpected spin effects have been discovered, such as the large spin-spin force in high-$P_\perp^2$ proton-proton elastic scattering.[1] Recent Brookhaven Alternating Gradient Synchrotron (AGS) measurements[2] of the analyzing power A in $p + p_\uparrow \rightarrow p + p$ at 28 GeV/c in the $P_\perp^2$ region up to 6.6 (GeV/c)^2 have also shown very large and unexpected effects. Such one-spin experiments study the spin-orbit interaction by measuring the analyzing power, which is sometimes called the polarization. We recently scattered the new AGS 16.5-GeV/c polarized proton beam from our polarized proton target and measured the pp elastic-scattering cross section in pure initial spin states at $P_\perp^2 = 2.2$ (GeV/c)^2. We detected the elastic-scattering events using a double-arm spectrometer consisting of magnets and scintillation-counter hodoscopes. In this first spin-spin experiment above ZGS energies, we found no evidence for strong energy dependence of the spin-spin correlation parameter A_{nn} in this medium-$P_\perp^2$ region.

The experiment was run at the AGS using an accelerated polarized proton beam of about 7×10^9 protons/pulse at 16.5 GeV/c. We used an extracted beam in the D beam line with an intensity of up to 3×10^9 protons per 2.4-sec pulse and scattered it from our polarized proton target (PPT). We used steering magnets which were servo-coupled to a split-plate ion chamber near the PPT to reduce the horizontal beam motion. The beam position and the 12 mm × 10 mm full width at half maximum ($H \times V$) spot size at our PPT were monitored continuously by three segmented-wire ion chambers (SWIC's), and the beam position was kept centered to within 0.5 mm. The relative beam intensity was measured using an ion chamber and three scintillation-counter telescopes M, N, and K, which counted the particles produced by the beam. A radiochemical foil calibration was run to determine the absolute calibration.

To accelerate polarized protons in the AGS it was necessary to make major hardware modifications in almost every part of the accelerator, as shown in Fig. 1. A new polarized H^- ion source was constructed, which now operates at a record 25 μA. A 200-MHz radio-frequency quadrupole (RFQ) was constructed to replace the Cockcroft-Walton 760-keV preaccelerator. This was the first RFQ ever used with an operating accelerator. It was necessary to pass

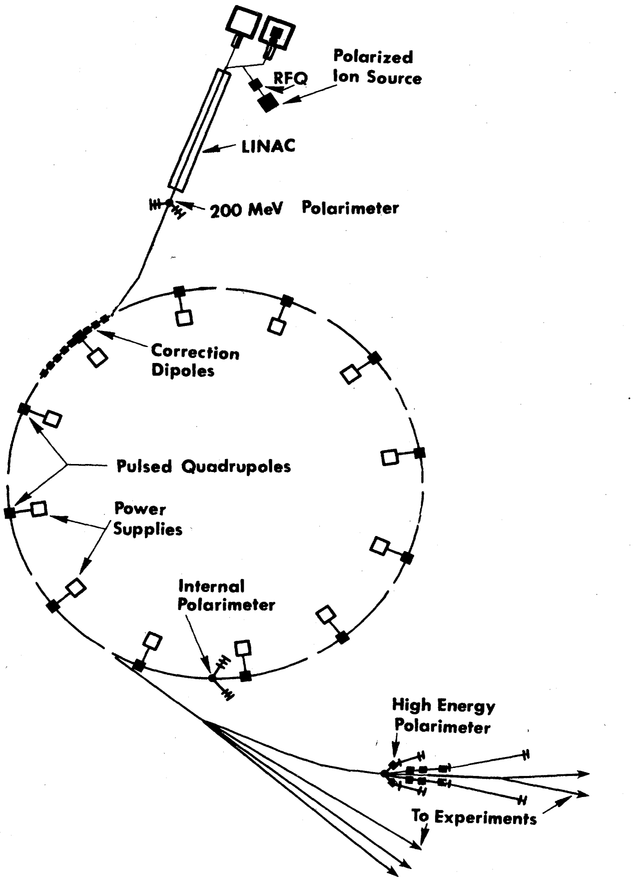

FIG. 1. Diagram of the AGS showing those areas where modifications were made to allow the acceleration of polarized protons.

about 30 strong depolarizing resonances during the main-ring acceleration cycle. The three strong intrinsic resonances were jumped with eight fast-pulsed quadrupole magnets which shifted the vertical betatron tune with a 1.6-μsec rise time. Almost 30 strong imperfection resonances were corrected with the appropriate harmonic produced by the 96 correction dipole magnets. A new type of strong depolarizing resonance was discovered and overcome near 15 GeV/*c*. The 200-MeV polarimeter measured the beam polarization at the end of the linac. The fast internal polarimeter measured the relative polarization during the AGS acceleration cycle. The high-energy polarimeter shown in Fig. 2 measured the absolute polarization by observing the left-right asymmetry in proton-proton elastic scattering at $P_\perp{}^2 = 0.3$ $(\text{GeV}/c)^2$, where A was taken to be[3] $(4.6 \pm 0.4)\%$. We reached a maximum polarization of about 40% at 16.5 GeV/*c* with a maximum accelerated intensity of about 10^{10} protons per pulse. The average beam polarization was $(31 \pm 3)\%$ for our data run. A detailed paper on the AGS polarized proton beam is being prepared by the Argonne-Brookhaven-Michigan-Rice-Yale polarized-beam collaboration.

The incident proton beam was scattered from the Michigan polarized proton target[4] (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. The high field and low temperature polarized the electrons in the target beads. The microwaves induced a hyperfine transition which transferred the electron polarization to the protons while the NMR system measured the proton polarization. The proton polarization was reversed by switching the microwave frequency between $\nu_e + \nu_p$ and $\nu_e - \nu_p$ where $\nu_e = 2\mu_e B/h$.

We used a new type of polarized-target beads provided by D. H. Hill and M. Krumpolc.[5] These 85% ethylamine/15% borane ammonia beads doped with EHBA-Cr(V) gave an initial polarization of 76% with our beam intensity of a few 10^9. These beads have a hydrogen content of 16% by weight. We continuously monitored radial variations in P_T using two independent 106.8-MHz NMR coils of different radii, which were calibrated in special runs with the microwaves and beam turned off. The thermal-equilibrium proton polarization is then given by the Boltzmann distribution

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

There is a ±3% absolute uncertainty in P_T caused by the

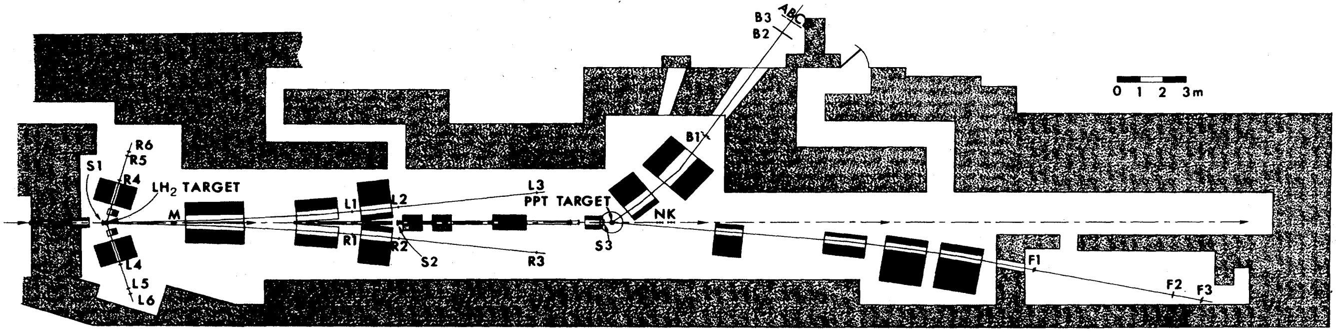

FIG. 2. Typical layout of the experiment. The polarimeter uses a liquid-hydrogen target to measure the left-right asymmetry in *pp* elastic scattering. The polarized proton beam was scattered in the vertically polarized proton target (PPT) and the elastic events were detected by the spectrometer which contains magnets for momentum analysis and the *F* and *B* scintillation-counter hodoscopes. The *M*, *N*, and *K* counters are intensity monitors, while the S_1, S_2, and S_3 SWIC's monitored the beam's position, size, and angle.

temperature uncertainty and electronic drifts. The average target polarization was $(66 \pm 3)\%$.

Elastic-scattering events were detected by the double-arm *FB* spectrometer shown in Fig. 2. The angles and momenta of both outgoing protons were measured using six magnets and the forward and backward scintillation-counter hodoscopes. A *pp* elastic-scattering event was 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 momentum bite was about $\Delta P/P \simeq \pm 5\%$ while the four (10 in.×14 in.) B_3 counters and the four (3.75 in.×5.5 in.) F_3 counters each defined a center-of-mass solid angle of about 4.2×10^{-4} sr. The other counters were overmatched to allow for beam divergence, magnet variations, multiple Coulomb scattering, and finite target size. Accidental coincidences were continuously monitored by delayed *FB* coincidence circuits. We collimated the magnet apertures with lead to reduce the single-arm rates and thus the accidental rate, which was about $\frac{1}{2}\%$. The data at each $P_\perp^2$ point were corrected using the measured accidental rate.

We covered a $P_\perp^2$ range of about 0.46 $(\mathrm{GeV}/c)^2$ with our four-channel hodoscope. 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 1.086 ± 0.002 and we multiplied the raw data by this factor.

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

$$N(ij) = E(ij)/I(ij) \quad . \tag{2}$$

For each (beam, target) spin state (ij), $E(ij)$ is the number of *FB* events corrected for accidentals and nonhydrogen background and $I(ij)$ is the relative beam intensity obtained by averaging the monitors *M*, *N*, *K*, and Ion. We used the *F* and *B* single-arm rates to check further the monitor consistency. The spin-spin correlation parameter A_{nn} and the analyzing power A were obtained from our measured values of $N(ij)$ using the equations

$$\begin{aligned}
A_{nn} &= \frac{1}{P_BP_T}\left[\frac{N(\uparrow\uparrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)+N(\downarrow\downarrow)}{N(\uparrow\uparrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)+N(\downarrow\downarrow)}\right] \ , \\
A_B &= -\frac{1}{P_B}\left[\frac{N(\uparrow\uparrow)+N(\uparrow\downarrow)-N(\downarrow\uparrow)-N(\downarrow\downarrow)}{N(\uparrow\uparrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)+N(\downarrow\downarrow)}\right] \ , \\
A_T &= -\frac{1}{P_T}\left[\frac{N(\uparrow\uparrow)-N(\uparrow\downarrow)+N(\downarrow\uparrow)-N(\downarrow\downarrow)}{N(\uparrow\uparrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)+N(\downarrow\downarrow)}\right] \ .
\end{aligned} \tag{3}$$

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

Our results for proton elastic scattering at 16.5 GeV/c and $P_\perp^2 = 2.2$ $(\mathrm{GeV}/c)^2$ are listed below along with our estimated uncertainty, which includes both statistical and systematic errors:

$$A_{nn} = (6.1 \pm 3.0)\% , \quad A_B = (4.2 \pm 2.0)\% , \quad A_T = (4.6 \pm 1.5)\% . \tag{4}$$

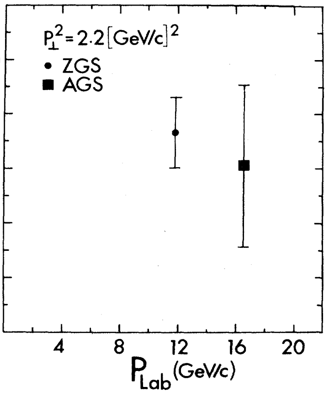

FIG. 3. Plot of the spin-spin correlation parameter A_{nn} as a function of incident laboratory momentum for *pp* elastic scattering at $p_\perp^2 = 2.2$ $(\mathrm{GeV}/c)^2$. The error bars include both statistical and systematic errors.

The estimated systematic error in A_T is $\pm 0.7\%$, because problems such as beam motion are not signal-averaged away by pulse-to-pulse beam-spin flipping, as they are for A_B and A_{nn}. Note that A_B and A_T, which are, respectively, measurements of A with the polarized beam and the polarized target, are equal within our errors. This provides a good test of our systematic uncertainty.

The new result on A_{nn} is plotted in Fig. 3 along with the 12-GeV/c ZGS point.[6] An interesting feature of the data is that in this medium-$P_\perp^2$ region A_{nn} seems to be roughly equal to its 7.3% value at 12 GeV/c. For many years it was widely believed that spin effects would decrease with energy and become quite unimportant at high energy.

The striking structure observed in various high-$P_\perp^2$ spin experiments[1,2] cannot be explained by present theories of strong interactions, such as perturbative QCD. The rapid increase in spin-spin effects discovered[1] at the ZGS occurs exactly at the start of the large-$P_\perp^2$ hard-scattering region. The huge and unexpected increase in A at very large $P_\perp^2$ found at the AGS occurs in the same hard-scattering region. Thus it seems very probable that these dramatic spin effects are associated with the onset of some hard-scattering mechanism. We hope to soon increase the intensity of the AGS polarized proton beam and then to study spin-spin effects in this unexplored large-$P_\perp^2$ region.

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