Energy Dependence of Spin Effects in $p_\uparrow + p_\uparrow \rightarrow p + p$

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(Received 6 May 1986)

We measured the analyzing power A and the spin-spin correlation parameter A_{nn}, in large-$P_\perp^2$ proton-proton elastic scattering, using a polarized-proton target and the polarized-proton beam at the Brookhaven Alternating-Gradient Synchrotron. We also used our polarimeter to measure A at small $P_\perp^2$ at 13 GeV with good precision and found some deviation from the expected $1/P_{\rm lab}$ behavior. At 18.5 GeV/c we found $A_{nn} = (-2 \pm 16)\%$ at $P_\perp^2 = 4.7$ (GeV/c)^2. Comparison with lower-energy data from the Argonne Zero-Gradient Synchrotron shows a sharp and surprising energy dependence for A_{nn} at large $P_\perp^2$.

PACS numbers: 13.85.Dz, 13.88.+e

Polarized proton beams and polarized-proton targets allow the direct study of spin effects in high-energy strong interactions. Since the polarized-proton beam first operated 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.[1,2] Recent Brookhaven Alternating-Gradient Synchrotron (AGS) measurements[3] of the analyzing power A in $p + p_\uparrow \rightarrow p + p$ at 28 GeV/c in the $P_\perp^2$ region up to 6.5 (GeV/c)^2 have also shown large one-spin effects. In 1984 we scattered the new AGS 16.5-GeV/c polarized proton beam from our polarized-proton target and measured A_{nn} in $p_\uparrow + p_\uparrow \rightarrow p + p$ at a fairly small $P_\perp^2$ with limited precision.[4] The energy, intensity, and polarization of the AGS polarized beam have now all increased significantly. These increases allowed us to study p-p elastic scattering in pure initial-spin states at $P_{\rm lab} = 18.5$ GeV/c and $P_\perp^2 = 4.7$ (GeV/c)^2. We found that the spin-spin correlation parameter A_{nn} appears to change rapidly with energy at this fixed $P_\perp^2$ value.

The experiment was run at the AGS with an accelerated polarized-proton beam of about 1.8×10^{10} protons per pulse at 13, 16.5, 18.5, and 22 GeV/c, with polarizations varying between 40% and 65%. We used an extracted beam in the D beam line with an intensity of up to 8×10^9 polarized protons per 2.2.-sec pulse and scattered it from the University of Michigan's polarized-proton target (PPT) as shown in Fig. 1. Steering magnets were servo-coupled to a split-plate ion chamber to reduce the horizontal beam motion. The beam position and the 13×13-mm^2 FWHM ($H \times V$) spot size at our PPT were monitored continuously by four segmented wire ion chambers (SIC's), and the average beam position was kept centered to within ± 0.2 mm. The relative beam intensity was measured with an ion chamber and three scintillation-counter telescopes M, N, and K, which counted secondary particles.

The acceleration of polarized protons in the AGS required major hardward modifications in almost every part of the accelerator. A polarized-H$^-$ ion source was constructed, which now operates at 25 μA.[5] A 200-

MHz radio-frequency quadrupole (RFQ) was built to replace the Cockcroft-Walton 760-keV preaccelerator. During each main-ring acceleration cycle, as the energy γ increased, there were about forty strong depolarizing resonances, which occurred whenever $G\gamma$ became equal to any horizontal-magnetic-field frequency $[G=(g-2)/2$ is 1.79 for a proton]. The five strong intrinsic resonances ($G\gamma=0+\nu$, $12+\nu$, $36-\nu$, $24+\nu$, and $48-\nu$) were jumped with ten fast-pulsed quadrupole magnets which shifted the vertical betatron tune ν with a 1.6-μsec rise time. About 35 strong imperfection resonances ($G\gamma=6,7,\ldots,40,41$) were corrected with the appropriate harmonic of horizontal field produced by 95 correction dipole magnets. We discovered that some of the strong depolarizing resonances could be corrected with either their primary harmonic (e.g., the 27th harmonic for $G\gamma=27$) or by use of a harmonic which beats[6] against an integer multiple of the AGS periodicity of 12 [e.g., the 9th harmonic for $G\gamma=27$ since $9=(3\times 12)-27$]. We also discovered that a 20% polarization loss near 14 GeV/c appears to be caused by interference between the $G\gamma=36-\nu$ intrinsic depolarizing resonance and the $G\gamma=27$ imperfection resonance. By using slow quadrupoles to shift the tune ν from its normal value of 8.75, we were able to separate these two resonances partially. This significantly reduced the polarization loss, allowing a beam polarization of about 50% up to high energy.

A 200-MeV polarimeter measured the beam polarization at the end of the linac. A fast internal polarimeter measured the relative polarization during the AGS acceleration cycle. The high-energy polarimeter shown in Fig. 1 measured the absolute polarization by observing the left-right asymmetry in proton-proton elastic scattering at $P_\perp^2=0.3$ (GeV/c)^2. The maximum polarization in the AGS was about 65% at 13 GeV/c, about 50% at 18.5 GeV/c and about 46% at 22 GeV/c with a peak accelerated intensity of about 2.1×10^{10} protons per pulse. The vertical bends in the D line caused a 5% polarization loss; our average beam polarization was (35 ± 3)% for the main data run at 18.5 GeV/c.

The polarized-proton beam was scattered from the polarized-proton target[7] (PPT). This target used the dynamic nuclear polarization technique at a temperature of 0.5 K produced by a ^{3}He-^{4}He mixture evaporation cryostat. Ammonia (NH_3) target beads, which have a free-proton density of about 0.1 g/cm^3, were contained in a cylindrical copper cavity 29 mm in diameter by 40 mm long. The 2-mm-diam NH_3 beads were irradiated at 90 K with about 5×10^{16} electrons/cm^2 from the Massachusetts Institute of Technology Bates linac to produce radiation damage centers with spin-unpaired electrons.[8] A 2.5-T magnetic field and the 0.5-K temperature polarized these electrons in our PPT. Microwaves of about 70 GHz were used to transfer the electron polarization to the free hydrogen protons. We continuously monitored the target polarization P_T using a 107-MHz NMR system with a ± 3% absolute uncertainty. The maximum target polarization was about 70% and the average polarization was (51 ± 3)%

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 by use of six magnets and the forward and backward eight-channel scintillation-counter hodoscopes. A p-p elastic-scattering event was defined by a sevenfold FB coincidence between the appropriate channels of the $F=F_0F_1F_2F_3$ arm and the $B=B_1B_2B_3$ arm. The momentum bite ($\Delta P/P$) was about ± 5%, while the four (25×35 cm) B_3 counters and the four (7.5×14 cm) F_3 counters each defined a center-of-mass solid angle of about 10^{-4} sr. The F_2 and B_2 counters were each split in half vertically, giving eight-channel resolution. The other counters were overmatched to allow for beam divergence, magnet variations, multiple

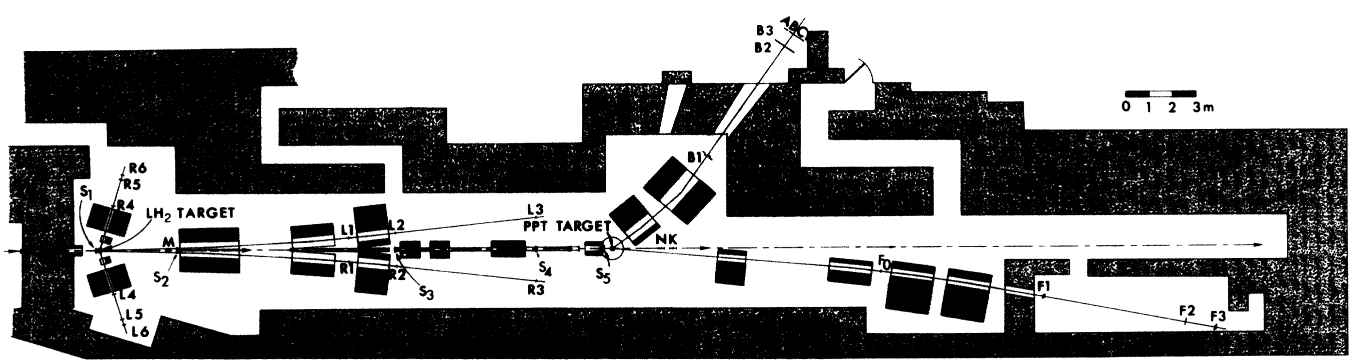


FIG. 1. Layout of the experiment. The polarimeter on the left used a liquid-hydrogen target to measure the left-right asymmetry in p-p elastic scattering. The polarized-proton beam then scattered in the vertically polarized-proton target (PPT) and the elastic events were detected by the spectrometer 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, S_4, and S_5 segmented wire ion chambers monitored the beam's position, size, and angle.

Coulomb scattering, and finite target size. Accidental coincidences were continuously monitored by several delayed FB coincidence circuits. The data at each $P_\perp^2$ point were corrected by use of the measured accidental rate of about 0.1%.

We covered a $P_\perp^2$ range of about 0.6 $(\mathrm{GeV}/c)^2$ with our eight-channel hodoscope. We varied the coincidence logic timing and the magnet currents about the calculated values to assure that we had a clean elastic signal at the correct $P_\perp^2$ value. We measured the background rate for nonhydrogen events by replacing the normal PPT beads with Teflon beads which contain no hydrogen. We corrected the data by the measured nonhydrogen background correction factor of 1.15 ± 0.03 at the large-$P_\perp^2$ 18.5-GeV/c point and of 1.07 ± 0.01 at the smaller-$P_\perp^2$ points.

The polarized-proton beam was scattered from the polarized-proton target in the horizontal plane in each transverse beam spin state [$i = \uparrow$ or $\downarrow$ (up or down)] and each transverse target spin state ($j = \uparrow$ or $\downarrow$). We then obtained the normalized event rates $N(i,j)$ by measuring the quantities

$$N(ij) = E(ij)/I(ij). \tag{1}$$

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

$$A_{nn} = \frac{1}{P_B P_T}\left[\frac{N(\uparrow\uparrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow) + N(\downarrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow) + N(\downarrow\downarrow)}\right], \quad A_B = -\frac{1}{P_B}\left[\frac{N(\uparrow\uparrow) + N(\uparrow\downarrow) - N(\downarrow\uparrow) - N(\downarrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow) + N(\downarrow\downarrow)}\right],$$

$$A_T = -\frac{1}{P_T}\left[\frac{N(\uparrow\uparrow) - N(\uparrow\downarrow) + N(\downarrow\uparrow) - N(\downarrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow) + N(\downarrow\downarrow)}\right], \tag{2}$$

where P_B and P_T are respectively the beam and target polarizations. The minus signs occur because our forward protons scatter to the right, which is opposite to the Ann Arbor convention.

Our results for proton elastic scattering are listed in Table I along with our estimated uncertainty, which includes both statistical and systematic errors. Note that A_B and A_T, which are respectively measurements of A with the polarized beam and with the polarized target, are generally equal within our errors. This provides a good test of our systematic uncertainty. A is the error-weighted average of A_B and A_T.

The A_{nn} data at small $P_\perp^2$ agree well with the 12-GeV/c ZGS data.[1] The small-error 13-GeV/c point at $P_\perp^2 = 1.5$ $(\mathrm{GeV}/c)^2$, taken together with previous 16.5-GeV/c data[4] at $P_\perp^2 = 2.2$ $(\mathrm{GeV}/c)^2$, suggest that A_{nn} is independent of energy at medium $P_\perp^2$. The high-precision measurement of A_T at 13 GeV/c was used to calibrate the beam polarization by constraining A_B to be equal to the measured value of A_T. This allowed us to measure A at $P_\perp^2 = 0.3$ $(\mathrm{GeV}/c)^2$ simultaneously using the high-energy polarimeter. The beam polarization at 18.5 GeV was obtained from the high-energy polarimeter by our interpolating A to be $(4.0 \pm 0.3)\%$ at $P_\perp^2 = 0.3$ $(\mathrm{GeV}/c)^2$. Our new 13-GeV/c datum point at $P_\perp^2 = 0.3$ $(\mathrm{GeV}/c)^2$ agrees with the 12-GeV/c data of Kramer *et al.*[9] and the 14-GeV/c data of Borghini *et al.*,[10] but does not agree with the 12-GeV/c data of Borghini *et al.*[11] Our new measurement seems to disagree with the possible $1/P_{\mathrm{lab}}$ dependence[12] of A at small $P_\perp^2$. The possible deviation from $1/P_{\mathrm{lab}}$ behavior is supported by an experiment done with our internal polarimeter which shows no variation in the measured asymmetry above 6 GeV/c, except for the sharp polarization loss near 14 GeV/c discussed earlier.

The new large-$P_\perp^2$ result on A_{nn} at $P_{\mathrm{lab}} = 18.5$ GeV/c is plotted in Fig. 2 along with lower-energy ZGS points.[2] The most notable feature of this plot is that at a fixed $P_\perp^2$ of 4.7 $(\mathrm{GeV}/c)^2$, A_{nn} has a very strong dependence on incident energy. This sharp change in A_{nn} is quite surprising. Several theoretical models predicted oscillatory behavior in A_{nn}, but none predicted that it would change in this way. Troshin and Tyurin[13] predicted that at a fixed angle of 90° c.m., as the energy is increased, A_{nn} would have a damped oscillation about the value $\frac{1}{3}$. They calculated that A_{nn} (90°

TABLE I. Data on A and A_{nn}.

P_{lab} (GeV/c)	$P_\perp^2$ [$(\mathrm{GeV}/c)^2$]	A_B (%)	A_T (%)	A (%)	A_{nn} (%)
13	0.3	4.7 ± 0.3	$\cdots$	4.7 ± 0.3	$\cdots$
13	1.5	Set equal to A_T	13.0 ± 0.6	13.0 ± 0.6	8.6 ± 0.9
16.5	1.6	9 ± 3	15 ± 4	11 ± 2	5 ± 5
18.5	4.7	-2 ± 9	2 ± 6	1 ± 5	-2 ± 16

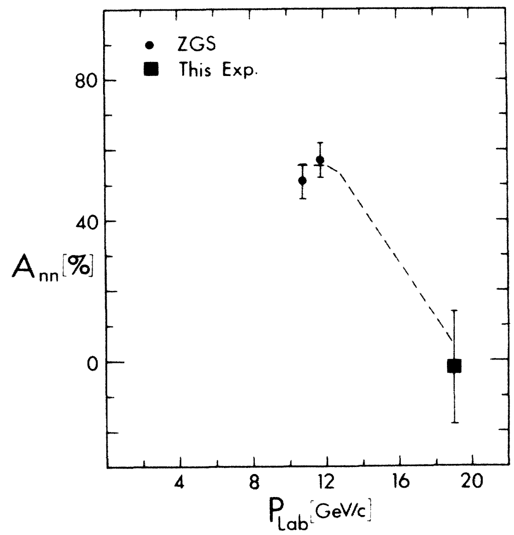


FIG. 2. Plot of the spin-spin correlation parameter A_{nn} as a function of incident laboratory momentum for proton-proton elastic scattering at $P_\perp^2 = 4.7$ (GeV/c)^2. The error bars include both statistical and systematic errors. The dashed line is a hand-drawn curve to guide the eye.

c.m.) would reach a minimum value of about 20% at 17 GeV/c. Brodsky, Carlson, and Lipkin[14] suggested that the 90° c.m. p-p cross section oscillates about their predicted s^{-10} behavior and then suggested that the behavior of A_{nn} is a reflection of this oscillation. it is not yet clear how these and other[15,16] fixed-angle predictions of oscillatory behavior are related to our observed fixed-$P_\perp^2$ behavior.

Another explanation of the possibly zero A_{nn} comes from comments made independently by Bethe[17] and Weisskopf[18] when the large spin-spin effects were first seen at the ZGS in 1978. They noted that at 12 GeV/c, the large A_{nn} values only appeared near 90° c.m. and thus might be due to particle identify effects near 90° c.m. rather than large $P_\perp^2$. We then did an experiment[2] where we held the scattering angle fixed at 90° c.m. and varied $P_\perp^2$ by varying the incident energy. We found that the large spin-spin effects occurred at exactly the same $P_\perp^2$ in both the 90° c.m. fixed-angle experiment and the 12-GeV/c fixed-energy experiment. This conclusively demonstrated that large spin-spin effects only occurred when $P_\perp^2$ was large. However, all of the large-$P_\perp^2$ ZGS data were fairly near to 90° c.m. The new AGS point at $P_\perp^2 = 4.7$ (GeV/c)^2, where $\theta_{\text{c.m.}}$ is 49°., is the first large-$P_\perp^2$ measurement of A_{nn} far from 90° c.m. Perhaps large $P_\perp^2$ and proximity to 90° c.m. are *both* required for large spin-spin effects to occur. This could be tested with the AGS polarized beam by measuring 90° c.m. elastic scattering near 18.5 GeV/c.

Another possibility is that spin effects decrease at high energy as predicted by many perturbative QCD models. This explanation must assume that 18.5 GeV/c is high enough to reduce the spin-spin effects while 12 GeV/c is not. Moreover, the large one-spin effects recently found at the AGS[3] at 28 GeV/c and $P_\perp^2 = 6.5$ (GeV/c)^2 disagree with the $A = 0$ prediction of perturbative QCD models and thus cast doubt on the applicability of perturbative QCD at 18.5 GeV/c and $P_\perp^2 = 4.7$ (GeV/c)^2. Now that the AGS polarized beam has reached 22 GeV/c with 46% polarization, we hope to extend these measurements to 22 GeV/c to determine if A_{nn} stays near zero, oscillates up to become large and positive again, or becomes negative for the first time.

We would like to thank Dr. D. I. Lowenstein and the many members of the Brookhaven AGS staff who helped in commissioning the AGS polarized-proton beam. We are grateful to Dr. G. T. Danby, Dr. G. Glass, Dr. Y. Y. Lee, and Dr. J. B. Roberts for their help with the earlier stages of this experiment. We thank the staff of the Massachusetts Institute of Technology Bates linac for their help with our bead irradiation. This work was supported by a research contract from the U.S. Department of Energy.

[1]D. G. Crabb *et al.*, Phys. Rev. Lett. **41**, 1257 (1978); K. Abe *et al.*, Phys. Lett. **63B**, 239 (1976); J. R. O'Fallon *et al.*, Phys. Rev. Lett. **39**, 733 (1977).

[2]E. A. Crosbie *et al.*, Phys. Rev. D **23**, 600 (1981).

[3]P. R. Cameron *et al.*, Phys. Rev. D **32**, 3070 (1985); P. H. Hansen *et al.*, Phys. Rev. Lett. **50**, 802 (1983); D. C. Peaslee *et al.*, Phys. Rev. Lett. **51**, 2359 (1983).

[4]K. A. Brown *et al.*, Phys. Rev. D **31**, 3017 (1985).

[5]J. Alessi *et al.*, in Proceedings of the Workshop on Polarized Targets and Sources, Montana, Switzerland, 1986, edited by S. Jaccard and S. Mango (to be published).

[6]K. M. Terwilliger *et al.*, IEEE Trans. Nucl. Sci. **32**, 2635 (1985).

[7]J. A. Bywater *et al.*, unpublished.

[8]D. G. Crabb *et al.*, in *Proceedings of the Fourth International Workshop on Polarized Target Materials and Techniques, Bad Honnef, Germany, 1984*, edited by W. Meyer (University of Bonn, Federal Republic of Germany, 1984), p. 7; S. Brown *et al.*, *ibid.*, p. 66; P. R. Cameron *et al.*, *ibid.*, p. 143.

[9]S. L. Kramer *et al.*, Phys. Rev. D **17**, 1709 (1978).

[10]M. Borghini *et al.*, Phys. Lett. **36B**, 501 (1971).

[11]M. Borghini *et al.*, Phys. Lett. **24B**, 77 (1967).

[12]J. Antille *et al.*, Nucl. Phys. **B185**, 1 (1981); H. A. Neal, in *High Energy Physics with Polarized Beams and Targets*, edited by M. L. Marshak, AIP Conference Proceedings No. 35 (American Institute of Physics, New York, 1976), p. 1; D. G. Crabb, private communication.

[13]S. M. Troshin and N. E. Tyurin, J. Phys. (Paris), Colloq. **46**, C2-235 (1985).

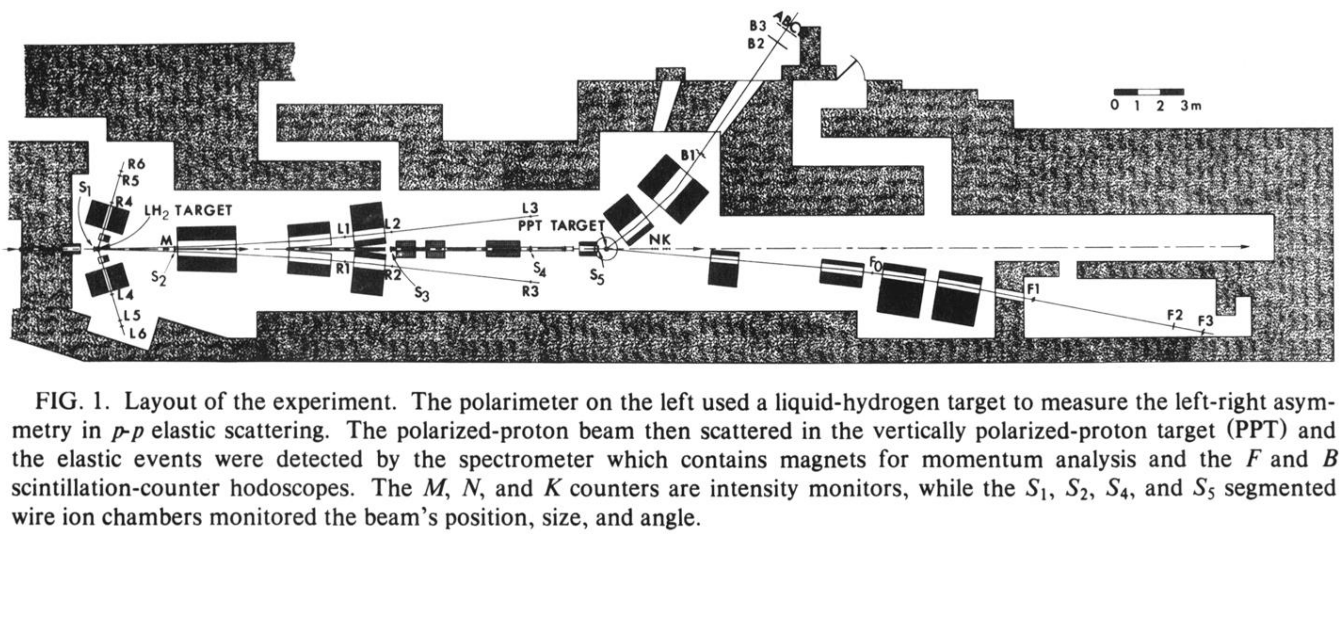
[14]S. J. Brodsky, C. E. Carlson, and H. J. Lipkin, Phys. Rev. D **20**, 2278 (1979).

[15]G. F. Wolters, Phys. Rev. Lett. **45**, 776 (1980).

[16]A. W. Hendry, Phys. Rev. D **23** 2075 (1981).

[17]H. A. Bethe, private communication.

[18]V. F. Weisskopf, private communication.



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