Measurements of spin parameters in p-p elastic scattering at 6 GeV/c

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(Received 5 March 1982)

We measured the differential cross section for proton-proton elastic scattering at 6 GeV/c, with both initial spins oriented normal to the scattering plane. The analyzing power A shows significant structure with a large broad peak reaching about 24% near $P_\perp^2=1.6$ (GeV/c)^2. The spin-spin correlation parameter A_{nn} exhibits more dramatic structure, with a small but very sharp peak rising rapidly to about 13% at 90$^\circ_{\text{c.m.}}$. This sharp peak may be caused by particle-identity effects.

INTRODUCTION

From 1973 until its turnoff in October 1979 the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory was the only accelerator in the world capable of accelerating polarized protons to GeV energies. The ZGS ultimately reached an intensity of 9×10^{10} polarized protons per pulse, with 70% polarization, and a maximum beam momentum of 12.75 GeV/c.[1–3] This polarized proton beam, used along with polarized proton targets, has allowed many detailed studies of spin-spin effects in p-p elastic scattering.[4] With the beam and target spins oriented normal to the scattering plane, many measurements were made of the spin-spin correlation parameter A_{nn} and the analyzing power A. For the early experiments the polarized-beam momentum was limited to 6 GeV/c, and the intensity was well below 10^{10} per pulse. Thus the experimenters concentrated on the momentum-transfer region $P_\perp^2<2$ (GeV/c)^2 where the high cross sections allowed reasonable data collection rates. Miller *et al.*[5] obtained relatively complete A and A_{nn} angular distributions at laboratory momenta of 2, 3, and 4 GeV/c and a partial distribution at 6 GeV/c. Our group had somewhat more extensive data at 6 GeV/c,[6,7] but not a full angular distribution.

When polarized protons could be accelerated to 11.75 GeV/c we concentrated on this energy. The increasing beam intensity let us extend our measurements to higher $P_\perp^2$,[8] and we obtained a full angular distribution at 11.75 GeV/c.[9] The A_{nn} behavior at 11.75 GeV/c showed quite dramatic structure at large $P_\perp^2$, rising abruptly from about 10% at $P_\perp^2=3.6$ (GeV/c)^2 to 60% at $P_\perp^2=5.09$ (GeV/c)^2. We also investigated the fixed-angle behavior of the spin-spin interaction at 90° c.m. by varying the ZGS momentum from 1.75 to 12.75 GeV/c.[10] A_{nn} again exhibited remarkable structure in the high-momentum-transfer region. When plotted against $P_\perp^2$, the 90° c.m. data exactly matched the behavior observed earlier at 11.75 GeV/c. This identical behavior strongly suggests that this huge and unexpected spin-spin effect is directly caused by hard scattering of the proton's constituents.

It would have been extremely valuable to obtain many complete spin angular distributions over the entire energy range of the ZGS. However, with the limited ZGS lifetime we decided to concentrate on extending our previous 6-GeV/c measurements to obtain a full angular distribution of high-precision 6-GeV/c data on A and A_{nn}. This new data complements other spin measurements made at 6 GeV/c.[11] Further data above 6 GeV/c must await the acceleration of polarized protons at the Brookhaven AGS or KEK.

POLARIZED PROTON BEAM

A schematic diagram of the ZGS indicating the modifications which were made to accelerate polarized protons[1–3] is shown in Fig. 1. In the polarized ion source, thermal hydrogen-gas molecules were dissociated into hydrogen atoms which passed through a sextupole magnet. The inhomogeneous magnetic field used the Stern-Gerlach effect to separate the atoms according to their electron spin state. Those atoms with their electron spin pointing along the magnetic field were focused by the sextupole field and continued into the rf transition stage, while the electron-spin-antiparallel atoms were defocused and lost. The remaining beam of neutral hydrogen atoms had their electrons totally polarized and their protons totally unpolarized. A weak dc magnetic field in the rf stage separated the energy levels of the two remaining proton spin states. An rf field then polarized the protons by inducing transitions from one of these occupied states which flipped both the electron and proton spins. The direction of polarization was determined by selecting the appropriate transition with the correct rf frequency and dc magnetic field. The polarization direction was changed on alternate pulses. The electrons were subsequently stripped off in the ionizer stage, which emitted a beam of 20-keV polarized protons. Following acceleration to 750 keV in the Cockcroft-Walton accelerator and to 50 MeV in the linear accelerator

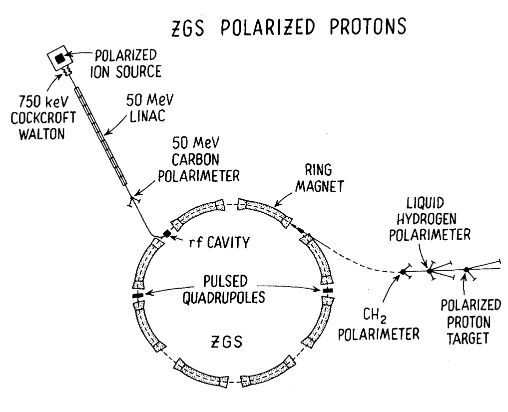

FIG. 1. Schematic diagram of the ZGS operating with a polarized beam.

(LINAC), the polarization of the protons was measured in a 50 MeV p-carbon scattering polarimeter, placed at the end of the LINAC.

The protons were accelerated in the ZGS with their spins oriented vertically. The ZGS ring magnets had very uniform vertical fields, which helped to preserve the polarization. However, the ZGS did have some vertical focusing due to the wedge shaped octant magnet edges, which created quadrupole-type horizontal fields. Because of the protons' vertical oscillations about the median plane these horizontal fields could depolarize the protons' spin. A very significant depolarizing resonance occurred whenever the protons saw these horizontal fields with a frequency equal to the protons' Larmor precession frequency. These intrinsic depolarizing resonances occured at energies which depended on the frequency of the vertical betatron oscillations. In the ZGS these intrinsic resonances could be crossed with minimal depolarization by rapidly pulsing a pair of special quadrupole magnets, which shifted the vertical betatron oscillation frequency quickly through the resonance before much depolarization could occur. Polarization losses due to the imperfection depolarizing resonances associated with field imperfections were minimized by briefly pulsing a horizontal magnetic field. By minimizing the measured depolarization, this correction field was experimentally tuned to exactly compensate the imperfection fields.

Relative measurements of the polarization of the extracted proton beam were made rapidly with a simple CH_2 target polarimeter. This fast polarimeter was calibrated against the slower but absolutely calibrated liquid-hydrogen target polarimeter discussed below.

EXPERIMENT

A detailed description of our experimental procedure was given earlier,[7] so we will discuss it only briefly. The experimental layout is shown in Fig. 2, where the 6-GeV/c vertically polarized protons from the ZGS came from the left. The protons passed through the polarimeter which measured the beam polarization, and then scattered from the vertically polarized proton target (PPT). The double-arm spectrometer, constructed of magnets and scintillation counters, detected the elastically scattered protons. The spin dependence of the differential elastic cross section was obtained by alternating the direction of the beam and target polarizations, so that the event rate was measured in each of the four spin states ↑↑, ↑↓, ↓↑, and ↓↓. Frequent spin flipping of both the beam and target strongly discriminated against most experimental biases.

High-energy polarimeter

The beam polarization was determined by measuring the asymmetry between the left and right scattering from the liquid-hydrogen target shown in Fig. 2. The beam polarization P_B was given by

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

where L and R were the event rates for the scattering of the forward proton to the left and right, and A was the analyzing power for $p+p \rightarrow p+p$ at the polarimeter's scattering angle. These L and R rates were measured using two matched double-arm spectrometers with momentum-analyzing magnets, run in series to minimize left-right experimental biases. In each spectrometer both the scattered and the recoil protons were detected by scintillation-counter telescopes. The elastic signal was obtained by analyzing the momentum of both the scattered and recoil protons to a precision of about 6%. The beam intensity was monitored by a scintillation-counter telescope M, shown in Fig. 2. Beam steering and alignment problems could cause systematic errors, so we carefully monitored the beam position at several points to a precision of about 1 mm using the segmented wire ion chambers (SWIC's) shown in Fig. 2.

In principle, if the beam direction is precisely known, a single spectrometer would be an adequate polarimeter, since the average beam polarization can also be found from

$$P_B = \frac{1}{A}\frac{L(\uparrow)-L(\downarrow)}{L(\uparrow)+L(\downarrow)} .$$

However, small deviations in the beam position or detector efficiency can cause first-order errors in the measurement of P_B in a single polarimeter. Such errors are removed by using a polarimeter containing two symmetric spectrometers. Other systematic errors were minimized by switching the beam polarization on alternate pulses. The present data were taken with the polarimeter set at $P_\perp^2 = 1.0\ (\mathrm{GeV}/c)^2$ where A was taken to be 0.144 ± 0.009.[7] The error in A includes estimated systematic uncertainties. The measured beam polarization averaged 68% for the entire experiment.

Polarized proton target

The polarized beam was focused to a 2.4-cm-diameter spot-size (full width at half maximum) on the 2.9-cm-diameter polarized proton target (PPT) shown in Fig. 2. A schematic diagram of the PTT and the ^{3}He-^{4}He cryostat is shown in Fig. 3.[12] The PPT contained frozen beads of ethylene glycol doped with Cr(V) complexes. The beads were maintained at 0.5 K in the highly uniform 25-kG magnetic field. The unpaired inner-shell electrons in the Cr were highly polarized by this strong field and low temperature. The electron's polarization

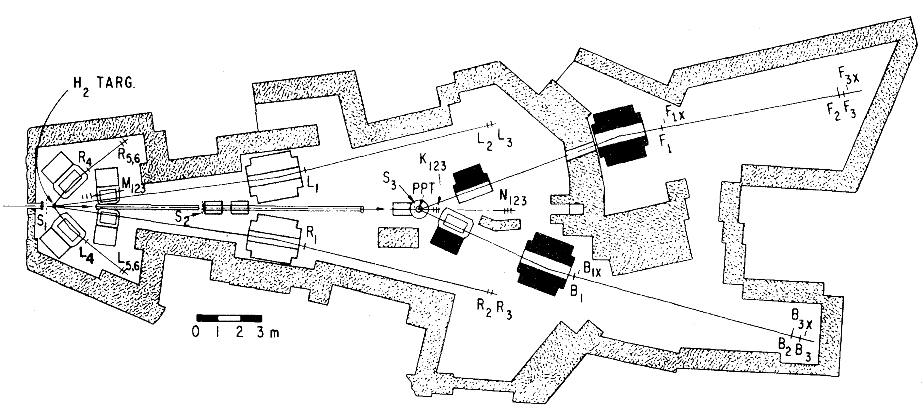

FIG. 2. Layout of the experiment. The polarized beam passed through the liquid-H_2 target and its polarization was measured by comparing the number of elastic p-p events seen in the L and R spectrometers of the polarimeter. The beam then scattered in the polarized proton target (PPT) and the elastic events were detected by the F and B or F_X and B_X scintillation hodoscopes. The M, N, and K counters were intensity monitors, while S_1, S_2, and S_3 monitored the beam's position, size, and angle.

was then transferred to nearby protons by the hyperfine transition caused by the 70-GHz microwaves. The target polarization P_T was measured by two NMR coils and monitored continuously. An absolute measurement of P_T was obtained by calibrating the NMR coils, using the measured and calculated "thermal" proton polarization at a temperature T of about 1.0 K. The calculated thermal polarization with the microwaves turned off is given by

$$P=\frac{e^{+\mu B/kT}-e^{-\mu B/kT}}{e^{+\mu B/kT}+e^{-\mu B/kT}}\ .$$

The polarized target was annealed regularly to minimize the effects of radiation damage which reduced the beads' ability to polarize.[13] The annealing frequency varied between every 12 hours and every 5 days, depending on the beam intensity which ranged from about 10^9 to 10^{10} polarized protons per pulse. We obtained initial target polarizations of up to 80%, but P_T averaged 69% for the entire experiment because of this radiation damage.

Spectrometer

The elastic-scattering events from the PPT were detected by the double-arm spectrometer shown in Fig. 2. Each arm had two momentum-analyzing magnets and scintillation-counter telescopes which subtended a solid angle of up to 1.4 msr (c.m.). We obtained this large solid angle while maintaining good angle and momentum resolution by using two hodoscope channels (F-B and F_X-B_X in Fig. 2). By sweeping the magnet currents at each value of $P_\perp{}^2$, we found a prominent elastic signal on a background of about 1%.

We measured four elastic-event rates corresponding to the two beam and two target spin orientations ($\uparrow\uparrow$, $\uparrow\downarrow$, $\downarrow\uparrow$, and $\downarrow\downarrow$). Systematic errors were minimized by reversing P_B every pulse and P_T every few hours. Background rates were obtained by replacing the PPT beads with hydrogen-free teflon, which is otherwise similar to ethylene glycol. These measured background rates, which ranged from 2.7 to 4.8%, were subtracted from the data. The uncertainty in A and A_{nn} due to these background corrections was less than $\frac{1}{2}\%$. The background rates obtained from the teflon data give a better measurement of the inelastic contamination than measuring the size of the background in magnet curves as in our previous 6-GeV/c experiment.[6] Our accidental rates, of about 0.1%, were also measured and subtracted.

The spot size and the horizontal and vertical positions of the beam at the PPT were monitored by the SWIC's shown in Fig. 2. The intensity of the beam incident on the PPT was monitored by the N and K scintillation-counter telescopes. Both telescopes were mounted to detect particles scattered in the vertical plane and thus were rather insensitive to the spin orientation of the protons. Since measurements of spin asymmetries are very sensitive to intensity normalization, we averaged the different monitors to reduce sensitivity to beam steering and counter efficiency. Fortunately the sensitivity to the choice of monitor was generally less than the statistical errors.

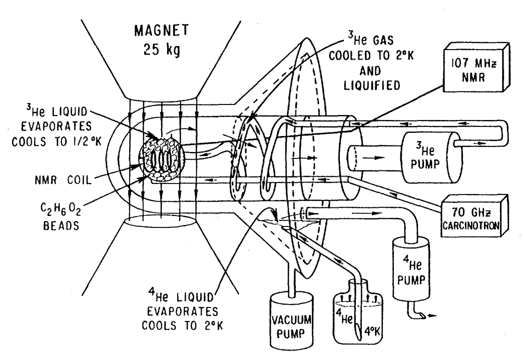

FIG. 3. Schematic diagram of the ^{3}He-^{4}He cryostat and polarized proton target.

ANALYSIS AND RESULTS

We measured the four normalized elastic-event rates $N(ij)$, where i and j, respectively, are the beam and target spin orientation, which could be either up or down ($\uparrow$ or $\downarrow$). Using these measured $N(ij)$ we obtained the beam and target analyzing powers, A_B and A_T, using the equations

$$A_B=\frac{N(\uparrow\uparrow)+N(\uparrow\downarrow)-N(\downarrow\uparrow)-N(\downarrow\downarrow)}{P_B\sum N_{ij}}\ ,$$

$$A_T=\frac{N(\uparrow\uparrow)-N(\uparrow\downarrow)+N(\downarrow\uparrow)-N(\downarrow\downarrow)}{P_T\sum N_{ij}}\ .$$

We also obtained the spin-spin correlation parameter A_{nn}, using

$$A_{nn}=\frac{N(\uparrow\uparrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)+N(\downarrow\downarrow)}{P_BP_T\sum N_{ij}}\ .$$

The above relations assume that the magnitudes of P_B and P_T are both independent of the spin direction.[7] Very small corrections were made to handle

TABLE I. Measurements of analyzing power obtained from beam and target in 6-GeV/c proton-proton elastic scattering. The errors are statistical.

$P_\perp^2$ [(GeV/c)^2]	A_B	A_T	A_B-A_T	$\frac{2(A_B-A_T)}{A_B+A_T}$
1.20	0.204±0.009	0.180±0.009	0.024±0.009	0.12±0.05
1.40	0.246±0.005	0.218±0.005	0.028±0.005	0.12±0.02
1.60	0.241±0.008	0.230±0.008	0.011±0.008	0.04±0.03
1.70	0.227±0.008	0.208±0.008	0.019±0.008	0.09±0.04
1.80	0.191±0.007	0.169±0.007	0.022±0.007	0.12±0.04
1.90	0.181±0.009	0.169±0.009	0.012±0.009	0.07±0.05
2.00	0.162±0.006	0.153±0.007	0.009±0.007	0.06±0.04
2.20	0.121±0.011	0.146±0.010	−0.026±0.011	−0.19±0.08
2.25	0.122±0.010	0.104±0.009	0.018±0.010	0.16±0.09
2.30	0.129±0.009	0.127±0.008	0.002±0.009	0.02±0.07
2.35	0.094±0.009	0.090±0.008	0.004±0.009	0.04±0.10
2.41	0.003±0.008	0.005±0.008	−0.002±0.008	

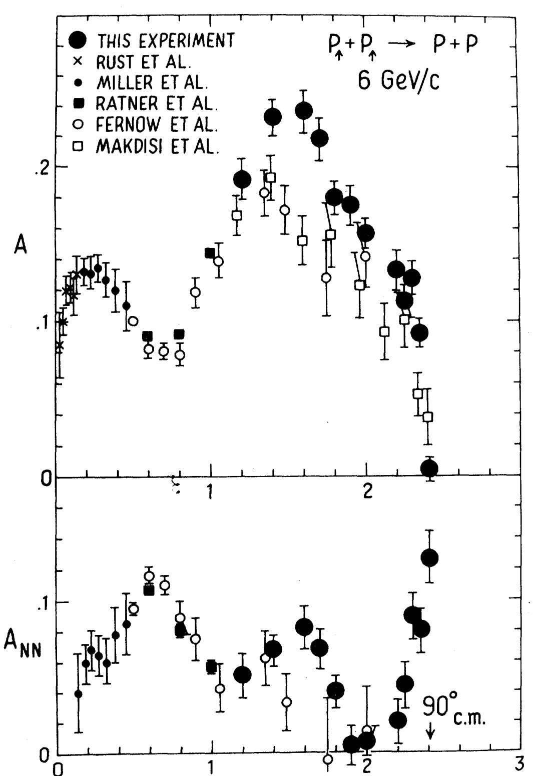

FIG. 4. Plots of the analyzing power A and spin-spin correlation parameter A_{nn} as a function of $P_\perp^2$ for pp elastic scattering at 6 GeV/c. The error bars for the present experiment include both statistical and systematic errors.

the observed P_B and P_T variations.

The results for A_B and A_T are listed in Table I. Only the statistical errors are shown. We can estimate the magnitude of the systematic errors since rotational invariance and identical particle symmetry require that $A_B=A_T$. Combining all our data in Table I we find that the value of $2(A_B-A_T)/(A_B+A_T)$ is 8.5% with a 1.2% statistical error. Our beam polarization determination is based on measurements of A at $P_\perp^2=1.0$ (GeV/c)^2 and has an estimated[7] systematic error $\Delta P_B/P_B=6\%$. We estimate our target polarization accuracy to be $\Delta P_T/P_T=4\%$. The 8.5% rela-

TABLE II. Measurements of the analyzing power and the spin-spin correlation parameter in 6-GeVc proton-proton elastic scattering as a function of $P_\perp^2$. Estimates of the systematic errors have been added in quadrature with the statistical errors.

$P_\perp^2$ [(GeV/c)^2]	A	A_{nn}
1.20	0.192±0.013	0.051±0.014
1.40	0.232±0.012	0.067±0.010
1.60	0.236±0.014	0.082±0.014
1.70	0.218±0.014	0.058±0.013
1.80	0.180±0.011	0.030±0.011
1.90	0.175±0.013	0.004±0.013
2.00	0.157±0.010	0.007±0.010
2.20	0.133±0.013	0.020±0.015
2.25	0.113±0.011	0.044±0.015
2.30	0.128±0.011	0.089±0.015
2.35	0.092±0.009	0.079±0.014
2.41	0.004±0.008	0.127±0.017

tive difference observed between A_B and A_T is thus somewhat large but is reasonably consistent with the calibration uncertainties in P_B and P_T. We take the simple average of A_B and A_T as our best estimate of A, and use the difference between A_B and A_T to estimate the systematic uncertainty. To be conservative we take $0.10A_{nn}$ and $0.05A$ to be the systematic errors of A_{nn} and A, respectively. These values of A and A_{nn} are presented in Table II, along with their estimated total errors.

DISCUSSION

Our data on A and A_{nn} at 6 GeV/c are plotted in Fig. 4 along with the results of some other recent experiments.[5,6,14,15] We are consistent with $A=0$ at $\theta_{\mathrm{c.m.}}=90°$, which is required by identical particle symmetry and rotational invariance. However in the region around $P_\perp^2=1.5$ (GeV/c)^2 there is an obvious disagreement between our present measurements of A and our previous results[6] and also those of Makdisi *et al.*[15] This difference is much larger than the present experiment's systematic uncertainty indicated by the A_B-A_T difference. In reexamining our earlier experiment[6] we find that we then had considerably less discrimination against inelastic background events which might have diluted the elastic events and thus reduced our measured value of A at large $P_\perp^2$.

At least two Regge models[16,17] fit the measured values of the 6 GeV/c A and A_{nn} at low $P_\perp^2$; however in the region above $P_\perp^2 \approx 1$ (GeV/c)^2 covered by this experiment no predictions were made. A recent eikonal model[18] is able to fit the gross features of the 6 GeV/c A and A_{nn} data over the full angular range.

Other approaches[19–24] focus on large momentum transfers where constituent interchange could be of major importance in exclusive reactions. These models generally are compared with higher-energy data and have difficulty predicting the fixed-angle energy dependence from basic principles since they rely on interference between competing processes whose relative strengths are poorly known. Also, since it is natural to assume helicity conservation at short distances, the constituent-type models favor a vanishing A, which obviously is not the case in this kinematical region.

Symmetry laws impose no constraints on A_{nn} and in fact, A_{nn} shows a rather sharp 90° c.m. peak. The spin-spin correlation parameter rises very dramatically from 2 to 13% over a $P_\perp^2$ range of only 0.2 (GeV/c)^2. A backward peak was also observed in A_{nn} at $P_{\mathrm{lab}}=3$ GeV/c, with somewhat larger errors.[5] This 6-GeV/c peak has no clear relation to the large and rapid increase in A_{nn} at 11.75 GeV/c which is mentioned in the Introduction; this occurs at larger $P_\perp^2$ of 3.6 to 5.09 (GeV/c)^2, and is much larger in magnitude, reaching 60%. Measurements of A_{nn} and between 6 and 12 GeV/c will be necessary to see if there is any connection between these two effects.

It seems possible that this sharp narrow 6-GeV/c peak is somehow associated with particle-identity effects near 90° c.m. It is certainly noteworthy that the width of the peak in A_{nn} is almost identical to the width of the dip in A as it goes sharply to zero at 90° c.m. The relation between these two widths may give some important information about the relation of spin to particle-identity effects.

ACKNOWLEDGMENTS

We would like to thank E. F. Parker and the ZGS staff for continuing the outstanding operation of the ZGS throughout its last year. We also thank J. Hauser, D. Jacobson, A. Chen, and M. Yatchman for their help running the experiment. This work was supported by a research grant from the U. S. Department of Energy.

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