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Spin Analyzing Power in *p-p* Elastic Scattering at 28 GeV/*c*

P. H. Hansen[(a)]
Niels Bohr Institute, DK-2100 Copenhagen, Denmark

and

J. R. O'Fallon[(b)]
Argonne Universities Association, Argonne, Illinois 60439

and

G. T. Danby, Y. Y. Lee, and L. G. Ratner
Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973

and

D. C. Peaslee
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

A. Perlmutter
Department of Physics and The Center for Theoretical Studies, University of Miami, Coral Gables, Florida 33128

and

P. R. Cameron, D. G. Crabb, M. Fujisaki,[(c)] M. E. Hejazifar, A. D. Krisch, A. M. T. Lin, S. L. Linn,[(d)] T. Shima,[(e)] and K. M. Terwilliger
Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48109
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The analyzing power, A, was measured in proton-proton elastic scattering with use of a polarized proton target and 28-GeV/c primary protons from the alternating-gradient synchrotron. Over the $P_\perp^2$ range of 0.5 to 2.8 (GeV/c)^2, the data show interesting structure. There is a rather sharp dip at $P_\perp^2=0.8$ (GeV/c)^2 corresponding to the break in the elastic differential cross section at the end of the diffraction peak.

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Scattering experiments with polarized proton beams and targets allow the study of spin effects in high-energy strong interactions. Any serious theory of strong interactions must now attempt to explain recently discovered unexpected spin effects such as the very large spin-spin forces in high-$P_\perp^2$ proton-proton elastic scattering.[1] We recently studied $p+p\to p+p$ at 28 GeV and made a high-precision measurement of the analyzing power, A, which is sometimes called the polarization. This one-spin experiment gives information about the spin-orbit interaction in the diffraction scattering region and the medium-$P_\perp^2$ region. We scattered a 28-GeV/c, high-intensity, unpolarized proton beam from our polarized proton target and measured the p-p elastic-scattering cross section in the two possible initial transverse spin states. 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 Alternating-Gradient Synchrotron (AGS) with use of 28-GeV/c primary protons in the new "D" beam line. This beam of about 3.5×10^{10} protons/pulse was separated from the main beam of about 7×10^{12} protons by a vertical electrostatic septum and then bent horizontally by 21° into our experimental area. Small variations in the AGS beam momentum together with the 21° bend caused significant variations in the beam position at our polarized-proton target (PPT). This movement was reduced by a fast steering magnet, which was servo coupled to a split-plate ion chamber placed just upstream of the PPT. A tight horizontal focus also reduced the horizontal beam motion. The beam position and the 10×12 mm full width at half maximum ($H\times V$) spot size at our PPT were monitored continuously by three upstream segmented wire ion chambers, and the beam position was kept centered to within ±0.5 mm. The beam intensity was measured with both an ion chamber and a secondary-emission chamber (SEC), which were calibrated by aluminum-foil irradiations. The relative beam intensity was also measured by the scintillation counter telescopes N and K, which counted particles produced at the PPT and by an upstream M telescope.

The incident proton beam was scattered from the PPT consisting of a ^{3}He evaporation cryostat inside a ^{4}He evaporation cryostat,[2] 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 long 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 transferred the electron polarization to the protons and the NMR system measured the proton polarization.

Initially we used standard ethanediol ($C_2H_6O_2$) target beads doped with Cr atoms. The Cr atoms contain unpaired inner-shell electrons which are 99.7% polarized at 0.5 K in a 25-kG field. The 70-GHz microwaves induce hyperfine transitions which transfer the electron polarization to the protons. The proton polarization was reversed by switching the microwave frequency between $\nu_e+\nu_p$ and $\nu_e-\nu_p$ where $\nu_e=\mu_eB/h$.

Radiation damage due to the high beam intensity seriously reduced the polarizability of the ethanediol beads. To maintain an average polarization of 65%, we had to anneal the target about twice a day and change the beads every few days. We therefore switched to chemically undoped crystalline ammonia (NH_3) beads, which become polarizable when irradiated. The beam radiation induces electron centers which allow the microwaves to polarize the protons.[3,4] Ammonia also contains 80% more hydrogen than ethanediol. The target polarization, P_T, was 45% after irradiation with 2×10^{15} protons/cm^2.

We continuously monitored radial variations in P_T using two independent NMR coils of different radii. A computer-driven voltage-controlled oscillator supplied 106.8-MHz rf with a sweep of ±200 kHz. We detected the real part of the NMR signal using a series-tuned Q meter and a phase-sensitive detector.[5] The polarization was proportional to the area under the NMR curve, which was amplified, digitized, and signal averaged. The proportionality constant was measured in calibration runs with the microwaves and beam turned off; the thermal-equilibrium proton polarization is then given by the Boltzmann distribution

$$P_T=\tanh(\mu_pB/kT). \quad (1)$$

There is a $\pm5\%$ uncertainty in P_T due mainly to the temperature uncertainty and electronic drifts.

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 with use of six magnets and the forward (F_1,F_2,F_3) and backward (recoil) (B_1,B_2,B_3) scintillation-counter hodoscopes. A p-p elastic scattering event was an 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, typically $\Delta P/P\simeq\pm5\%$, was defined by four horizontal channels in the F_1, F_3, B_1, and B_3 hodoscopes. Counters F_2 and B_2 were twofold vertical hodoscopes, which defined $\Delta\varphi$ and insured coplanar events. The four (10-in.$\times$17-in.) B_3 counters (B_{3a}, B_{3b}, B_{3c}, and B_{3d}) defined the center-of-mass solid angle of $\sim10^{-3}$ sr. The other counters were overmatched to allow for beam divergence, magnet variations, multiple Coulomb scattering, and finite target size.

The 0.5-in.-thick scintillators were connected to twelve-stage RCA 8575 phototubes via Lucite light guides. The last four dynodes were separately supplied with current to avoid saturation

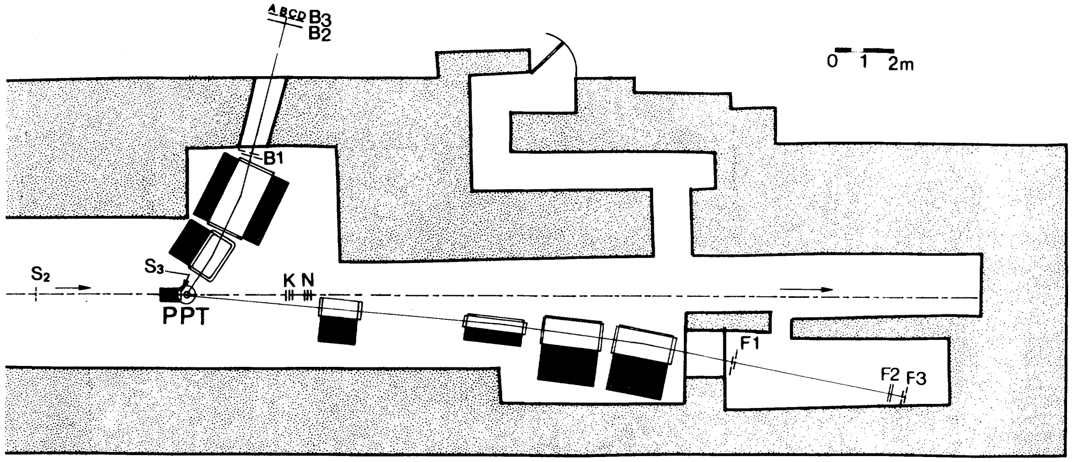

FIG. 1. Layout of the experiment. The unpolarized proton beam scattered in the vertically polarized-proton target (PPT) and the elastic events were detected by the F and B scintillation counter hodoscopes. The N and K counters were intensity monitors, while S_2 and S_3 were segmented wire ion chambers which monitored the beam's position, size, and angle.

due to our high rates. The phototube pulses were fed to 100-MHz discriminators and logic circuits, which were timed to identify elastic coincidences with a precision of ± 3 ns. The four different FB coincidence rates, the associated accidental rates, and all F and B singles rates were recorded with two independent sets of scalers. Accidental coincidences were continuously monitored by parallel FB coincidence circuits with each B channel delayed by the additional 225-ns period between AGS rf bunches. The accidental rate at each $P_\perp^2$ was typically less than 10%, and all data were corrected with measured values.

We covered the $P_\perp^2$ range of 0.5 to 2.8 $(\mathrm{GeV}/c)^2$ by varying the magnet currents without moving the detectors or magnets. At each $P_\perp^2$ setting, we adjusted and swept the coincidence logic timing and also adjusted and swept the magnet currents about the calculated values to assure a clean elastic signal at the selected $P_\perp^2$ value. The background rate for nonhydrogen events was measured by runs with the normal PPT beads replaced by Teflon beads, which contain no hydrogen. This nonhydrogen background rate was 20% at $P_\perp^2 = 1.95$ $(\mathrm{GeV}/c)^2$ and we corrected all data as indicated in Table I, using an extrapolation for the $P_\perp^2$ dependence of this background. We estimated[6] that the inelastic background is much smaller than the measured nonhydrogen background and thus no additional correction was made.

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

$$N(\uparrow) = \mathrm{Events}(\uparrow)/I(\uparrow),$$
$$N(\downarrow) = \mathrm{Events}(\downarrow)/I(\downarrow), \qquad (2)$$

TABLE I. Measurements of the analyzing power, A, in 28-GeV/c proton-proton elastic scattering as a function of $P_\perp^2$. Estimates of the systematic errors were added in quadrature with the statistical errors. The background correction factor for ethanediol was taken to be $1.13 + 0.13 P_\perp^2/1.95$ on the basis of the measured Teflon point at $P_\perp^2 = 1.95$ and earlier data (Ref. 1) on the $P_\perp^2$ dependence. The NH_3 background was experimentally determined as indicated.

$P_\perp^2$ $(\mathrm{GeV}/c)^2$	A uncorrected	Background correction factor	A
0.52	0.92 ± 0.21	1.17 ± 0.07	+1.1 ± 0.8
0.83	−2.72 ± 0.31	1.19 ± 0.06	−3.3 ± 0.8
0.83 NH_3	−3.09 ± 0.64	1.10 ± 0.03	
0.98	−1.36 ± 0.60	1.19 ± 0.06	−2.2 ± 0.9
0.98 NH_3	−3.81 ± 1.29	1.10 ± 0.03	
1.11	0.44 ± 0.88	1.21 ± 0.05	+0.5 ± 1.2
1.29	2.02 ± 1.17	1.21 ± 0.05	+2.4 ± 1.5
1.45	5.12 ± 1.18	1.23 ± 0.03	+6.3 ± 1.5
1.65	3.69 ± 1.31	1.23 ± 0.03	+4.5 ± 1.6
1.95	4.13 ± 1.01	1.26 ± 0.02	+5.2 ± 1.3
2.29	4.46 ± 1.30	1.29 ± 0.03	+5.8 ± 1.7
2.55	3.02 ± 1.53	1.29 ± 0.03	+4.9 ± 1.2
2.55 NH_3	4.63 ± 1.21	1.16 ± 0.03	
2.82 NH_3	5.92 ± 1.43	1.16 ± 0.03	+6.9 ± 1.7

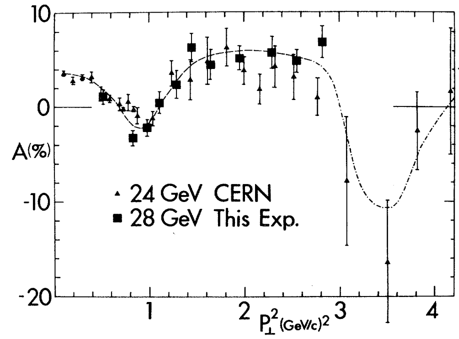

FIG. 2. Plot of the analyzing power A as a function of $P_\perp{}^2$ for pp elastic scattering at 28 GeV/c. The error bars for the present experiment include both statistical and systematic errors. The 24-GeV/c CERN data (Ref. 7) are also shown. The curve is a hand-drawn line to guide the eye.

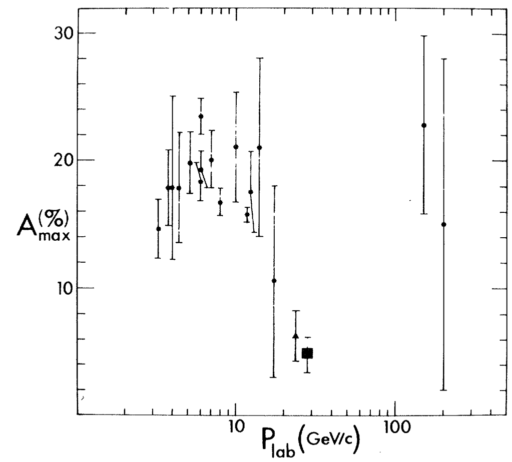

FIG. 3. The maximum value of the analyzing power, in the peak near $P_\perp{}^2 = 1.4$ (GeV/c)^2, plotted against the laboratory momentum for $p + p \to p + p$. Our point and the CERN point are respectively shown as a square and triangle. The other points were taken from the compilation in Antille *et al.* (Ref. 7).

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. We used the F and B single-arm rates to further check the monitor consistency. The analyzing power was obtained from our measured values of $N(i)$ with the equation

$$A = -\frac{1}{P_T}\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}. \tag{3}$$

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 statistical and systematic errors. The results are plotted in Fig. 2 along with the 24-GeV/c CERN data.[7] There is generally good agreement between the two experiments within errors. The most notable feature of our data is the sharp dip near $P_\perp{}^2 = 0.8$ (GeV/c)^2 where A drops to about -3%. The analyzing power then increases steadily reaching about 6% near $P_\perp{}^2 = 2.0$ (GeV/c)^2. Note that our data give no suggestion of a minimum near $P_\perp{}^2 = 2.2$ (GeV/c)^2.

The sharp dip in A near $P_\perp{}^2 = 0.8$ (GeV/c)^2 appears deeper in our data than in the CERN data. This dip may be growing sharper and deeper with increasing energy as suggested by the results of Fidecaro *et al.*[8] and Kline *et al.*[9] It is very interesting that the dip in A occurs near the sharp slope change in $d\sigma/dt$, at the transition from the "diffraction peak" to the medium-$P_\perp{}^2$ region.[10]

There appears to be significant energy dependence in the peak in A near $P_\perp{}^2 = 1.4$ (GeV/c)^2. The $P_\perp{}^2$ position of this peak does not vary significantly with energy; but the maximum value of A does. As suggested by the CERN data,[8] A_{max} drops sharply between 12 and 28 GeV, as shown in Fig. 3. This drop is somewhat surprising in view of the rather flat behavior in the 4- to 12-GeV range. It would be most interesting to study this energy dependence more carefully, since there is no theoretical prediction of this sharp structure in A_{max} centered near 6 GeV.

The current theories of strong interactions cannot yet explain the structure observed in high-$P_\perp{}^2$ spin experiments; nevertheless, some very striking effects have been observed. The sharp increase in spin-spin effects discovered at the zero-gradient synchrotron occurs exactly at the start of the large-$P_\perp{}^2$ hard-scattering region.[10] This strongly suggests that these spin effects are associated with the abrupt onset of a new scattering mechanism. The CERN data suggest a very deep dip in A near the same $P_\perp{}^2 = 3.5$ (GeV/c)^2, the start of the hard-scattering region. We plan to soon study this suggested sharp dip in A and to search for further spin effects in the totally unexplored hard-scattering region beyond $P_\perp{}^2 = 4$ (GeV/c)^2.

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(a)Present address: CERN, Geneva 23, Switzerland.

(b)Present address: Office of Advanced Studies and Department of Physics, The University of Notre Dame, Notre Dame, Ind. 46556.

(c)Present address: AEI Industries, Tokyo, Japan.

(d)Present address: Department of Physics, SUNY at Stony Brook, Stony Brook, N. Y. 11974.

(e)Present address: HEP Division, Argonne National Laboratory, Argonne, Ill. 60439.

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