Polarization Structure in p-p Elastic Scattering*

G. W. Abshire, C. M. Ankenbrandt,† R. R. Crittenden, R. M. Heinz,
K. Hinotani,‡ H. A. Neal,§ and D. R. Rust
Department of Physics, Indiana University, Bloomington, Indiana 47401
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We present here the results of an experiment to study the polarization in p-p elastic scattering at the incident momenta 5.15, 7.00, and 12.33 GeV/c, at t values ranging between -0.5 and -6.5 (GeV/c)^2. At each momentum we observe a relative maximum in the polarization around $t=-1.8$ (GeV/c)^2. At 12.33 GeV/c the data exhibit a double zero near $t=-2.4$ (GeV/c)^2 and another relative maximum near $t=-2.9$ (GeV/c)^2. The results are discussed in terms of the Chu-Hendry optical model.

In this Letter we present the results of an experiment performed at the Argonne National Laboratory zero-gradient synchrotron accelerator to make high-precision measurements of the polarization in p-p elastic scattering at large four-momentum transfers. Measurements were made at incident proton momenta of 5.15, 7.00, and 12.33 GeV/c at $|t|$ values extending to 6.5 (GeV/c)^2 at the highest momentum. To attain high-statistics data at such large $|t|$ values we have used, for the first time at high energies, a polarized-proton target in an external proton beam.

In recent years several intriguing dynamical effects have been observed in p-p elastic scattering. Allaby *et al.*[1] and Böhm *et al.*[2] have reported structure in the differential cross section near $t=-1$ (GeV/c)^2. A "break" in the 90° c.m. differential cross section was found around $t=-6.5$ (GeV/c)^2 by Akerlof *et al.*[3] Additional slope changes in the 90° cross section have been reported by Kammerud *et al.*[4] at $t\approx-0.8$ and -2.5 (GeV/c)^2. A minimum in the polarization near $t=-1$ (GeV/c)^2 has been observed by Neal and Longo[5] and by Parry *et al.*[6] Another minimum in the polarization near $t=-2.5$ (GeV/c)^2 was indicated in the work of Borghini *et al.*[7] A theoretical explanation of these rather spectacular effects is still not at hand.

One goal of the present experiment was to make a significant extension in the t range over which high-energy p-p polarizations are known. This extension is crucial to the testing of models which predict recurring structure in the polarization since, heretofore, the only firmly established minimum was at $t=-0.8$ (GeV/c)^2. Another goal of the experiment was the determination of the polarization at large $|t|$. Our initial results at 5.15 GeV/c have been presented elsewhere.[8]

A beam of 10^9–10^{10} protons per pulse was incident on a 2-in.-long ethylene-glycol polarized target. The beam was formed by using septum magnets to divert a fraction of the Argonne external proton beam No. 1 into a dispersive-optics transport line leading to the polarized target. The intensity and position of the beam at the target were monitored on a burst-to-burst basis with ionization counters and multiwire proportional chambers. In addition, six other independent detector systems, described in Ref. 8, were used to monitor the intensity of the beam.

The outgoing protons of an elastic event were detected in two multiwire-proportional-chamber spectrometers whose angular positions were remotely controlled (see Fig. 1 of Ref. 8). Each spectrometer consisted of four proportional chambers followed by an analyzing magnet and four additional proportional chambers. Each arm had six scintillation-counter planes, four trigger counters, and two hodoscopes. The times of flight for each arm and the relative time of flight were recorded for each trigger, with a resolution of about ±0.7 nsec. The spectrometers allowed a ±5% momentum determination to be made. This momentum resolution, a 3-mrad resolution on the effective opening angle, and the good time-of-flight resolution were severe constraints for eliminating nonelastic events. The p-p elastic polarization parameter was determined from the change in the relative differential cross section produced by a change in the sign of the target polarization. More details of the experimental layout and techniques may be found elsewhere.[8,9]

The ethylene-glycol polarized targets used in the experiment had a free-proton content of about 0.39 g/cm^2. Because of the high intensity of the incident beam it was necessary to change targets frequently and to monitor the target polarization carefully. The radiation damage to the polarizing centers caused the target polarization to vary according to the empirical relation $P = P_0 \exp(-\varphi/\varphi_0)$, where P_0 is the initial polarization, φ is the accumulated flux per square centimeter, and $\varphi_0 \approx 2 \times 10^{14}$ protons/cm^2. A nuclear magnetic resonance system was interfaced to our on-line PDP-15 computer to permit the periodic recording of the target polarization. The initial target polarization was typically 0.41. The target polarization could be determined to an accuracy of ±0.02.

The principal potential sources of background in the experiment were (a) inelastic events from the target and cryostat and (b) quasielastic events from bound protons in the target and cryostat assembly. Runs were made with the glycol target removed and also with dummy targets substituted for the glycol target. In addition, extensive Monte Carlo calculations were made to provide a consistency check on the quasielastic measurements.

Although the cross sections of interest were as low as 20 nb/(GeV/c)^2, it was possible in all cases to observe a clear elastic peak with an associated total background of less than 25%. Background subtractions were made assuming zero background polarization. The validity of this assumption was tested by studying the polarization of events just outside the elastic peak.

Several precautions were taken to minimize the possibility of false asymmetries. Checks were made to ensure that no significant asymmetries resulted from possible variations in the proportional-chamber or scintillation-counter efficiencies. Also various monitor ratios were checked continually to ensure that the monitor counters were completely ignorant of the target polarization. The beam position was restricted to a narrow range and constantly monitored. No geometrical changes were made in any part of the experimental layout between runs with positive and negative target enhancements. Typically thirty target-spin reversals were made at a single datum point. Such a large number of reversals rendered insignificant the effect of all other residual false asymmetries. We estimate the overall systematic uncertainty due to uncertainties in the target polarization and in the background subtraction to be less than 8% of the polarization.

The polarization results are given in Table I. The 5.15-GeV/c results are shown in Fig. 1(a) together with the results of Parry *et al.*[6] at the same momentum. The data indicate a minimum value of 8% in the polarization at $t = -0.8$ (GeV/c)^2, corresponding to the structure reported at lower momenta in Refs. 5 and 6. As $|t|$ increases the polarization climbs to a maximum value of 20% at $t = -1.8$ (GeV/c)^2. The polarization

TABLE I. Polarization results for p-p elastic scattering at 5.15, 7.00, and 12.33 GeV/c.

Lab momentum -- 5.15 GeV/c			Lab momentum -- 7.00 GeV/c			Lab momentum -- 12.33 GeV/c		
-t[(GeV/c)^2]	Polarization	Error	-t[(GeV/c)^2]	Polarization	Error	-t[(GeV/c)^2]	Polarization	Error
.540	.115	±.018	.582	.079	±.019	1.531	.141	±.043
.729	.076	±.013	.673	.078	±.025	1.730	.199	±.039
.943	.107	±.021	.770	.066	±.022	1.960	.189	±.039
1.181	.162	±.027	.873	.111	±.024	2.103	.108	±.053
1.440	.142	±.021	1.040	.078	±.015	2.159	.076	±.056
1.719	.198	±.024	1.157	.141	±.025	2.331	.015	±.062
1.836	.218	±.032	1.344	.169	±.030	2.508	.034	±.053
2.016	.163	±.033	1.476	.125	±.028	2.630	.048	±.060
2.201	.160	±.030	1.683	.201	±.022	2.754	.129	±.052
2.328	.130	±.024	2.053	.181	±.030	2.945	.164	±.072
2.456	.131	±.036	2.288	.137	±.036	3.140	-.008	±.059
2.652	.103	±.039	2.450	.167	±.031	3.830	-.007	±.083
2.987	.077	±.037	2.617	.161	±.030	4.572	-.092	±.116
3.331	.056	±.031	2.873	.093	±.029	5.361	.086	±.117
4.031	.004	±.028	3.318	.042	±.037	6.191	.277	±.139
			3.781	.080	±.036			
			5.245	.064	±.058			

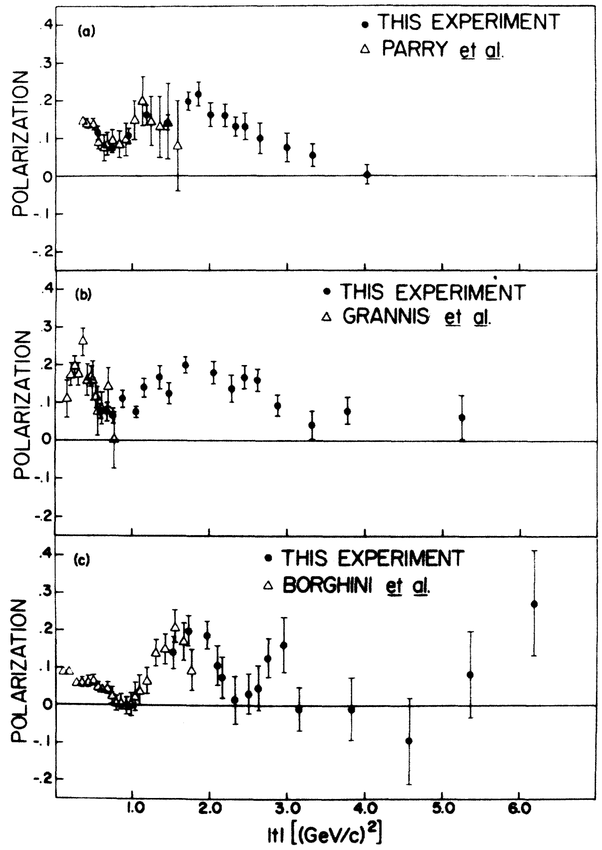

FIG. 1. Polarization in p-p elastic scattering: (a) 5.15 GeV/c, (b) 7.00 GeV/c, (c) 12.33 GeV/c.

then declines monotonically to a value consistent with 0% at $t = -4.03$ (GeV/c)^2, the 90° c.m. point.

The 7.00-GeV/c results are illustsrated in Fig. 1(b). The data begin at $t = -0.6$ (GeV/c)^2 at a polarization value of about 8%. Our data in conjunction with the low-t results of Grannis *et al.*[10] are consistent with the existence of a minimum at $t = -0.8$ (GeV/c)^2. As $|t|$ increases beyond 0.6 (GeV/c)^2 the polarization rises to a value of about 20% at $t = -2.0$ (GeV/c)^2, and then declines as $|t|$ increases further. There is a suggestion that a shoulder begins to develop near $t \simeq -3$ (GeV/c)^2.

In Fig. 1(c) our 12.33-GeV/c results are presented along with the 10.0-GeV/c results of Borghini *et al.*[7] The data exhibit substantial structure with minima in the polarization appearing at $t = -0.8$ and -2.5 (GeV/c)^2, and possibly a minimum near $t = -4$ (GeV/c)^2. In addition to the low-$|t|$ maximum, our data have maxima of 0.2 at $t = -1.7$ and -2.9 (GeV/c)^2.

The polarization minimum at $t = -0.8$ (GeV/c)^2 and the relative maximum near $t = -1.8$ (GeV/c)^2 appear to be more or less independent of the energy of the elastic p-p interaction, at least at intermediate energies. Also, a significant minimum in the polarization appears to develop near $t = -2.5$ (GeV/c)^2 as the momentum increases. We note[9] further that at large fixed $|t|$ values the decline of the polarization with increasing energy appears to be less rapid than that observed at low $|t|$.

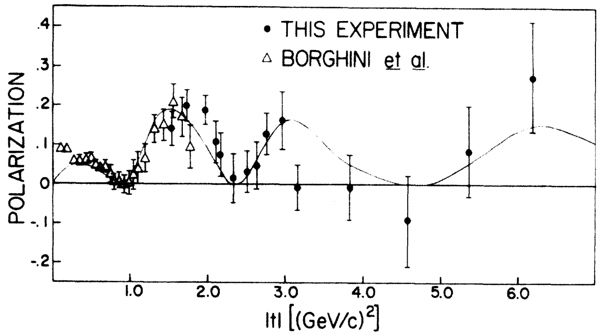

FIG. 2. The fit to the 12.33-GeV/c results using the optical model of Chu and Hendry.

It is difficult to explain the observed polarization structure in the framework of the Regge model. Indeed, on the basis of duality one is led to a Regge prediction of structureless p-p polarization unless unusual forms of the residue functions are admitted. In the optical model of Chu and Hendry[11] the helicity-nonflip amplitudes are assumed to receive contributions from partial waves corresponding to impact parameters $b < R$, where R is a characteristic radius. The single-flip amplitudes are assumed to be due to partial waves near the boundary of the interaction region of radius R. Double-flip amplitudes are neglected. Taking the gray-disk approximation of this model, one would expect polarizations of the form

$$P \sim [J_1(R\sqrt{-t})]^2/R\sqrt{-t}$$

where $R \approx 0.9$ fm. One prediction is that there are double zeros located at $t \cong -0.7$, -2.5, -5.2, ... (GeV/c)^2. This prediction[12] is quite consistent with our 12.33-GeV/c data, as is illustrated in Fig. 2. The fit shown is a simultaneous fit to the differential cross section, the total cross section, the ratio of the real to imaginary parts of the forward scattering amplitude, and the polarization. A more comprehensive examination of various model predictions for p-p elastic polarization is made by Hendry and Abshire.[13]

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†Present address: National Accelerator Laboratory, Batavia, Ill. 60510.

‡On leave from Tenri University, Tenri, Nara, Japan, during the 1972–1973 academic year.

§Alfred P. Sloan Foundation Fellow; presently Visiting Scientist at the Niels Bohr Institute, Copenhagen, Denmark.

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