Polarization and Angular Distributions in Elastic *pp* Scattering at 100 and 300 GeV

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Measurements of the polarization parameter and angular distributions in *pp* elastic scattering at incident energies of 100 and 300 GeV are reported. The data cover the kinematic range $0.18 < -t < 2.0$ GeV^2. They are found to be consistent with absorption-model predictions.

In the first polarized-target experiment at Fermilab we have measured the asymmetries and angular distributions in the elastic scattering of pions and protons from polarized protons. The pion data have already been reported.[1] We report here proton polarization and angular distribution data at incident energies of 100 and 300 GeV over a kinematic range $0.15 < -t < 2.0$ GeV^2, where t is the square of the four-momentum transfer. The data sets presented here are comprised of 520 thousand elastic events at 300 GeV and 370 thousand events at 100 GeV.

Regge-pole models have been formulated which accurately describe πp elastic polarization data[2]; these same models, however, are unable to account for the structure of the *pp* polarization.[3] The usual phenomenology with exchange degeneracy predicts a smoothly varying polarization without zeros for $-t$ less than a few GeV^2, in disagreement with the data throughout the energy range from 10 to 45 GeV.[4-6] Models which include absorptive corrections have been constructed which are able to fit existing data adequately below 100 GeV. Extension of the energy range of polarization data tests these models and permits further study of the structure in *pp* polarizations.

The double-arm spectrometer used in the experiment has been described in a preceding article[1]; we concentrate here on its modifications for an incident energy of 300 GeV. At 300 GeV the beam had a spot size at the target of 1×1 cm^2, with an angular divergence of less than ±0.1 mrad, and a momentum bite of $\pm1\%$. Spacings between elements on the forward arm at 300 GeV were twice the spacings at 100 GeV, while the recoil-arm configuration was unchanged. In this new configuration the acceptance of the apparatus was uniform for $0.35 < -t < 1.90$ GeV^2; at 100 GeV the acceptance was uniform for $0.20 < -t < 1.90$ GeV^2. At 100 GeV, the beam was monitored by a three-counter telescope aimed at the polarized proton target (PPT) from 100 mrad below the beam line. For the 300-GeV data, a second three-counter telescope was added, placed symmetrically at 100 mrad above the beam line. Typical beam intensities were 2×10^7 particles per pulse (ppp) at 100 GeV, and 5×10^7 at 300 GeV.

The 100-GeV data were collected in a single six-week run, while the 300-GeV data were collected in two six-weak runs. In the first of these two runs, data at high $-t$ and low $-t$ were collected simultaneously; in the second run with the emphasis on obtaining data at high $-t$, events in the region of high $-t$ were selected by the requirement of a scintillation counter in the forward-arm coincidence.

Possible transverse polarization components in the incident beam were eliminated by precessing them into the scattering plane at the PPT by four dipole magnets placed directly upstream of the PPT. Had the beam upstream of the PPT been polarized normal to the scattering plane, and the spin correlation parameter C_{NN} been large, the asymmetry measured with precession magnets energized would have been different from that with the magnets turned off. No difference was observed in the 300-GeV data. This test was not performed at 100 GeV.

The analysis of the present data was identical to the analysis of the πp data at 100 GeV.[1] Polar and azimuthal scattering angles for the particle trajectories on both arms, and the recoil momentum, were measured. Three independent values of four-momentum transfer, assuming elastic scattering, were calculated from the polar angles and from the recoil momentum, and compared by forming an average t and the associated

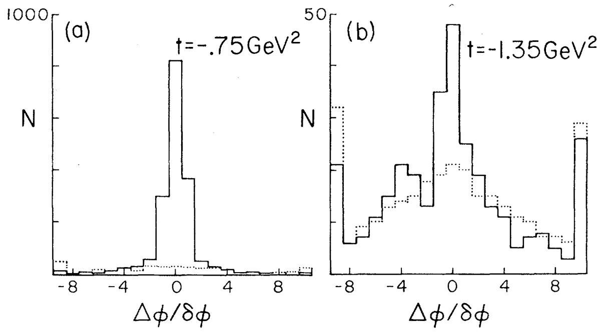

FIG. 1. Coplanarity distributions for two values of t at 300 GeV. The solid curves indicate the distributions for events with $\chi^2 < 2$, while the dotted lines indicate the distributions for events with $\chi^2 > 10$.

χ^2. The azimuthal angles with their combined measurement uncertainty $\delta\phi$ were used to form an estimator of the coplanarity of the trajectories of the particles in the initial and final states. Elastic events were taken to be events with small values of χ^2 ($\chi^2 < 2$), and small values of $\Delta\phi/\delta\phi$ ($|\Delta\phi/\delta\phi| < 2.5$). As examples of the quality of the analysis, we show in Fig. 1 distributions of $\Delta\phi/\delta\phi$ for $\chi^2 < 2$ at two values of t at 300 GeV. The dotted curves are the corresponding distributions for $\chi^2 > 10$ normalized to the numbers of events in the range $3 < |\Delta\phi/\delta\phi| < 9$.

Angular distributions are normalized to published data at $t = -0.55$ GeV^2 and at $t = -0.85$ GeV^2 for the 100- and 300-GeV data sets, respectively, and are shown in Fig. 2 with 1-standard-deviation statistical uncertainties. At 100 GeV our data agree with published data for small $-t$ and are statistically more precise for larger $-t$.[7] Our 300-GeV data are in agreement with those obtained at the CERN intersecting storage rings by Kwak *et al.*[8] with the minimum in the elastic differential cross section observed at $t = -1.5$ GeV^2. The smooth curves in Fig. 2 are the results of fits to the data as described below.

Results for the polarization parameters in pp scattering at 100 and 300 GeV are shown in Fig. 3; numerical values for the polarization are given in Table I. Included in the figure are the recent polarization data of Corcoran *et al.*[9] at 100 GeV, with which our data are consistent. The ratio of signal events to background events (nonelastic events) was typically 20:1 for $-t$ less than 0.5 GeV^2, and diminished to 0.8:1 at $t = -1.35$ GeV^2.

The normalization of beam flux for both sets of data was as described in Ref. 1; we have not in-

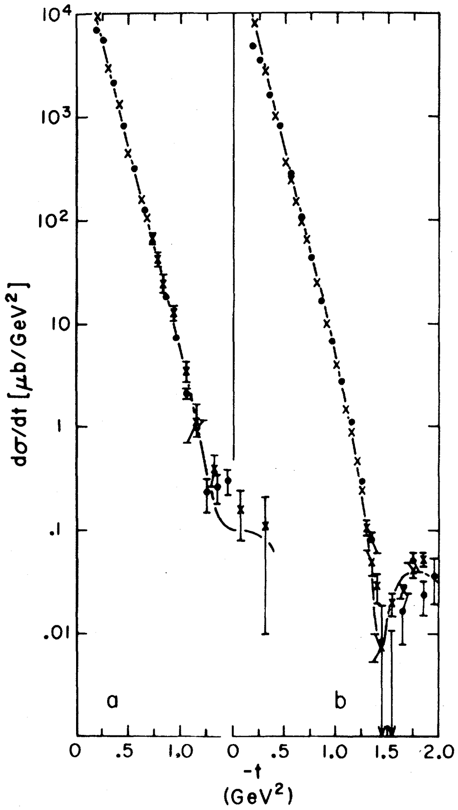

FIG. 2. (a) Differential-cross-section data at 100 GeV (dots) plotted with data from Ref. 7 (crosses). (b) Differential-cross-section data at 300 GeV (dots) plotted with data from Ref. 8 (crosses). Solid curves are fits to the data from a model described in text.

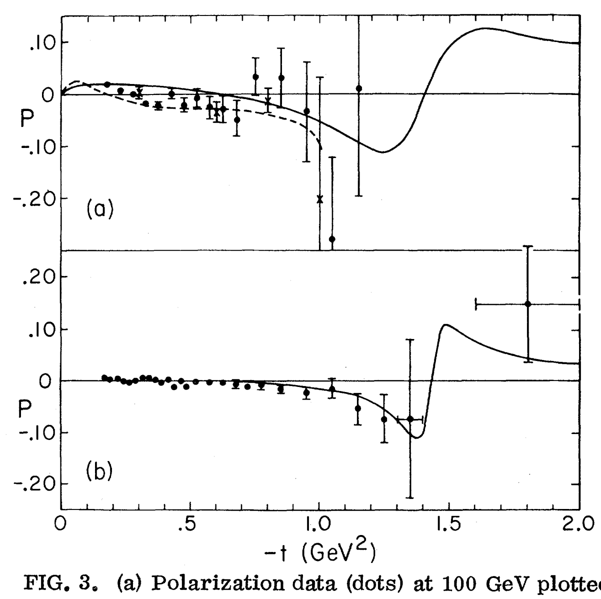

FIG. 3. (a) Polarization data (dots) at 100 GeV plotted with data from Ref. 9 (crosses). (b) Polarization data at 300 GeV. Solid curves are predictions of a model described in the text. Dashed curve is a prediction from Ref. 10.

TABLE I. Polarizations in pp scattering at 100 and 300 GeV.

-t	P
100 GeV	
0.15 - 0.20	.0177 ± .0055
0.20 - 0.25	.0076 ± .0047
0.25 - 0.30	.0032 ± .0055
0.30 - 0.35	-.0179 ± .0067
0.35 - 0.40	-.0225 ± .0085
0.40 - 0.45	-.0006 ± .0106
0.45 - 0.50	-.0213 ± .0133
0.50 - 0.55	-.0074 ± .0172
0.55 - 0.60	-.0265 ± .0220
0.60 - 0.65	-.0295 ± .0270
0.65 - 0.70	-.0485 ± .0350
0.7 - 0.8	.0326 ± .0357
0.8 - 0.9	.0295 ± .0567
0.9 - 1.0	-.0357 ± .0960
1.0 - 1.1	.0098 ± .2060
300 GeV	
0.150 - 0.175	.0118 ±.0083
0.175 - 0.200	.0034 ±.0053
0.200 - 0.225	.0069 ±.0052
0.225 - 0.250	-.0039 ±.0056
0.250 - 0.275	-.0076 ±.0064
0.275 - 0.300	-.0011 ±.0073
0.300 - 0.325	.0113 ±.0081
0.325 - 0.350	.0097 ±.0084
0.350 - 0.375	-.0025 ±.0089
0.375 - 0.400	-.0103 ±.0097
0.400 - 0.425	-.0006 ±.0114
0.425 - 0.450	-.0276 ±.0126
0.450 - 0.475	-.0037 ±.0142
0.475 - 0.500	-.0227 ±.0158
0.50 - 0.55	-.0046 ±.0132
0.55 - 0.60	-.0136 ±.0166
0.60 - 0.65	-.0102 ±.0094
0.65 - 0.70	-.0162 ±.0103
0.70 - 0.75	-.0241 ±.0123
0.75 - 0.80	-.0176 ±.0157
0.8 - 0.9	-.0339 ±.0156
0.9 - 1.0	-.0488 ±.0245
1.0 - 1.1	-.0277 ±.0368
1.1 - 1.2	-.1110 ±.0610
1.2 - 1.3	-.152 ±.096
1.3 - 1.4	-.15 ±.31
1.6 - 2.0	.294 ±.223

cluded an estimated normalization uncertainty of ±0.005 in the table. At low $-t$ the errors are dominated by systematic fluctuations in the monitor counts, while at larger $-t$ the errors are dominated by the statistical uncertainty in the numbers of events. A multiplicative uncertainty of 5% in the polarization scale due to the uncertainty in the target polarization has also not been included.

To obtain a quantitative understanding of the structure of the polarization in this energy regime, we have updated the Michigan absorption model[11] by including data not available when that work was published. Using the values given in Ref. 11 as the starting values of the free parameters in the model, we have obtained[12] reasonable fits to reported differential-cross-section and polarization data[4-8] above 6 GeV. The resulting predictions for the pp polarizations at 100 and 300 GeV are shown in Fig. 3. Also shown is the prediction at 100 GeV from the model of Irving,[10] which includes a "diffractive" helicity-flip amplitude. Both models appear to describe the data satisfactorily.

To summarize, we have presented new polarization and angular distribution data at 100 and 300 GeV, and found that the data are well fitted by an absorption model. The behavior of the polarization suggests two areas for further polarization measurements: the energy region from 20 to 40 GeV, where the structure of the polarization is changing from the double-zeros structure to a single-zero structure with negative polarization; and at energies above 100 GeV around the dip in the differential cross section, where many models predict large polarizations.

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Note added.—Recently published polarization-parameter measurement[13] at 150 GeV are more negative in the region $0.8 < -t < 1.4$ GeV^2 than the measurements reported here, both at 100 and 300 GeV.

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Test of the Okubo-Zweig-Iizuka Rule in ϕ Production

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We have measured the reaction $\pi^- p \to K^+K^-K^+K^- n$ at 22.6 GeV/c and detect strong φ signals in the K^+K^- effective-mass plots. We do not observe the expected Okubo-Zweig-Iizuka–rule suppression of the $\varphi\varphi n$ final state and conclude that the rule is working poorly in the observed production processes.

The Okubo-Zweig-Iizuka (OZI) rule[1] is an essential ingredient in the successful quark-model explanation of the decay of the φ, f', J/ψ, and ψ' resonances. In recent attempts[2] to extend the model to detailed predictions of the production of resonances, the OZI rule again plays an important part. Experimental studies of "forbidden" and "allowed" processes are required in order to shed some light on the precise nature of the rule. Perhaps the best available reactions for this purpose involve φ-meson production since its dominant ($s\bar{s}$) quark structure leads to inhibition of many exclusive channels[3]—for example, single or multiple φ production unaccompanied by strange particles is predicted to be suppressed in πp interactions.

We have studied the interaction

$$\pi^- p \to K^+K^-K^+K^- n \tag{1}$$

at 22.6 GeV/c. A major purpose of the experiment was to search for resonances in the $\varphi\varphi$ system. The results of that search were published earlier[4]; details were given of the apparatus and experimental procedure. Briefly, the Brookhaven National Laboratory multiparticle spectrometer was used to select and reconstruct events[5] for Reaction (1). A sensitivity of approximately 15 events/nb was achieved. The neutron-recoil cut defined for this paper is the same as used in Fig. 1(c) in Ref. 4; that is, a missing-mass-squared cut of < 2.0 GeV^2 was applied and the counters around the target were used as a veto.

We wish to consider the reactions

$$\pi^- p \to \varphi[K^+K^-]n, \quad \varphi \to K^+K^- \tag{2}$$

$$\pi^- p \to \varphi\varphi n, \quad \varphi \to K^+K^-, \quad \varphi \to K^+K^- \tag{3}$$

