Large-Angle π^- Proton Elastic Scattering at 14 and 23 GeV/c*

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The differential cross section for π^--p elastic scattering has been measured at 13.8 and 22.6 GeV/c up to $-t=5$ (GeV/c)^2. The dips in the angular distribution at $-t\approx 0.8$ and 2.8 (GeV/c)^2 previously observed at lower momenta become less prominent at higher momentum. The $-t=2.8$ (GeV/c)^2 dip is still observed at 13.8 GeV/c, but at 22.6 GeV/c it has become a sharp kink in the angular distribution. At large momentum transfers, $d\sigma/dt$ at fixed t is still decreasing with increasing s, but at a slower rate in the 14- to 23-GeV/c region than at lower momenta.

Previous experimental results on pion-proton[1-4] and proton-proton[5] elastic scattering have revealed structures in the angular distributions and a strong decrease of cross section with increasing momentum, and it is of interest to determine if the shapes and magnitudes of the cross sections are approaching limiting values as the momentum increases. Recent observations at the CERN intersecting storage rings[6] on proton-proton scattering at 1500-GeV/c equivalent momentum have shown a dip in the cross section at $-t$ ~1.4 (GeV/c)^2 that is much more pronounced than at conventional accelerator momenta. The present experiment studies the π^--p system, where previous detailed measurements were all below 10 GeV/c; we have now extended the incident-momentum range with measurements at 13.8 and 22.6 GeV/c.

The experimental layout is shown in Fig. 1. The angle and momentum of the scattered pion and the angle of the recoil proton were measured using some of the equipment of the Northeastern-Stony Brook group.[7] The pion beam was produced at 0° from a target in the slow extracted proton beam of the Brookhaven alternating-gradient synchrotron (AGS), and ~10^6 pions per AGS pulse were incident on the 24-in.-long liquid-hydrogen target. Beam and scattered particles were identified by threshold gas Cherenkov counters C_1 to C_5. Not shown are two counter hodoscopes giving information on incident particle momentum and direction.

The recoil-proton direction was determined by five magnetostrictive readout wire spark cham-

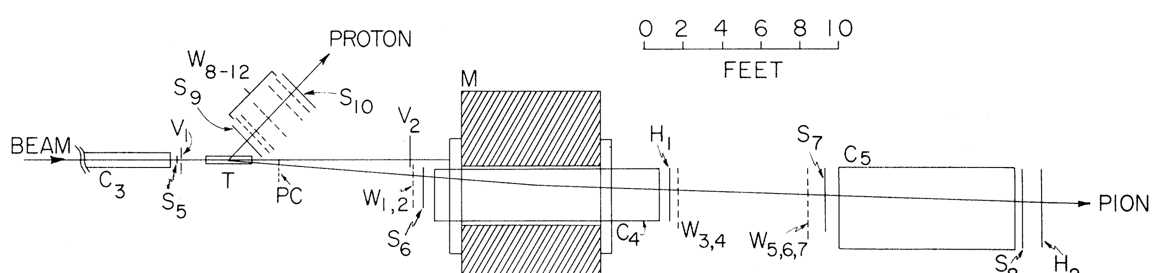

FIG. 1. Experimental layout. S_5–S_{10}, V_1, and V_2 are scintillation counters. H_1 and H_2 are scintillation-counter hodoscopes. C_3–C_5 are threshold gas Cherenkov counters. W_1–W_{12} are wire spark chambers. PC is a proportional chamber. M is a bending magnet. Scintillation counters S_1–S_4, threshold gas Cherenkov counters C_1 and C_2, and two scintillation-counter hodoscopes are in the beam upstream of the apparatus shown.

bers, W_8 to W_{12}; the scattered pion angle and momentum were determined by a system of seven wire spark chambers W_1–W_7, the 18-kG magnet M, and the proportional chamber PC (in use during most of the experiment). Each chamber gave two coordinates. Counter hodoscopes H_1 and H_2 were used only at 22.6 GeV/c.

The spark-chamber trigger was a triple coincidence between an incident pion (as signified by beam scintillation and Cherenkov counters), a count in the scintillation counters S_6, S_7, and S_8 in the forward arm, and S_9 and S_{10} in the recoil arm. In addition, there had to be no count in the veto counters V_1 and V_2; the former eliminated beam halo while the latter ensured an interaction in the hydrogen target and also eliminated most interactions producing more than one forward charged particle. At 22.6 GeV/c, only selected combinations of the counters in hodoscopes H_1 and H_2 were allowed for most of the data taking in order to reduce the trigger rate from nonelastic events. After each trigger, the information from the spark chambers and hodoscopes was read into a PDP-9 computer, which was used for monitoring the experiment, and then written onto magnetic tape for off-line analysis. The trigger rate was typically 10/AGS pulse of which 5 to 10% were elastic events.

The apparatus as shown in Fig. 1 covered the region $1 < -t < 6$ (GeV/c)^2 for 22.6 GeV/c and $0.7 < -t < 4.5$ (GeV/c)^2 for 13.8 GeV/c. Both the magnet and the recoil arm were moved to cover the region $0.3 < -t < 1.5$ (GeV/c)^2 at 22.6 GeV/c.

In the analysis, cuts were made to reject interaction points outside the beam-defining counter area and the hydrogen target. From the forward-arm information alone, the missing mass of the recoil system could be calculated, and all data showed a sharp peak at the proton mass. From the particle directions in both arms, the difference $\Delta\theta$ between the measured forward angle and that predicted from the recoil-particle angle by elastic kinematics was calculated; also the coplanarity of the event was determined. Histograms of the data as functions of $\Delta\theta$ or coplanarity show sharp elastic peaks sitting on slowly varying backgrounds. Figure 2(a) shows the coplanarity histogram for part of the data at 22.6 GeV/c and $-t > 3$ (GeV/c)^2 after applying cuts on missing mass and $\Delta\theta$. In this worst case we observe an elastic peak on an ~10% uniform background of inelastic events. In Fig. 2(b) we confirm empirically that this inelastic background is uniform by histographing events with missing

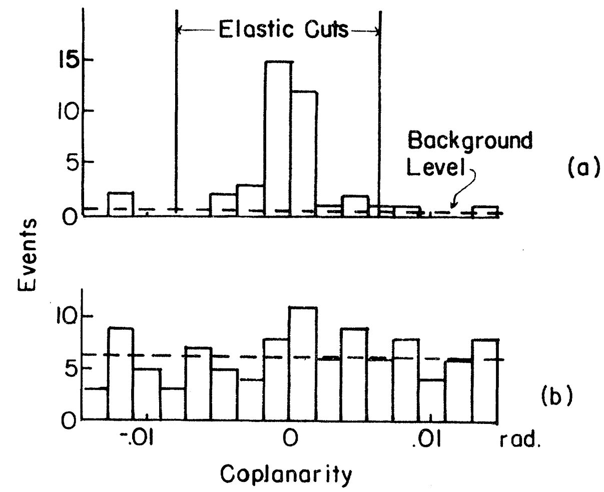

FIG. 2. (a) Coplanarity histogram for part of the data at 22.6 GeV/c and $-t > 3$ (GeV/c)^2 after making cuts on missing mass and $\Delta\theta$. Cross sections were determined from data between the two vertical lines. (b) As for (a), but for missing mass and $\Delta\theta$ just outside the elastic region.

mass just above the elastic peak and with $\Delta\theta$ close to, but outside of, the elastic peak.

In order to obtain cross sections, the geometrical acceptance was calculated by Monte Carlo means. The overall spark-chamber efficiencies for both sets of spark chambers were determined by preselecting elastic events without using information from the spark chambers in question. The forward-arm system was checked by selecting elastic events in $\Delta\theta$ and coplanarity using the recoil arm and the proportional chamber only. The recoil-arm system was checked by selecting elastic events using tight cuts on missing mass obtained from the fast arm only. The result was a systems efficiency of ~85% for either arm.

Cross sections were corrected by ~4% for trigger inefficiency, ~15% for particle absorption, ~2% for beam muon and electron contamination, ~1% for pion decay, 0 to 5% for electronic deadtime, and ~1% for the analysis cuts. Because of uncertainties in the corrections, we estimate that our normalization uncertainties are ±9% for the 13.8-GeV/c results and ±12% for the 22.6-GeV/c results.

Our results are given in Fig. 3; only relative errors are shown, and the normalization uncertainties are not included. In addition to our $\pi^- p$ results at 13.8 and 22.6 GeV/c, we show data[2,4] at 5 and 9.7 GeV/c. As a check on our absolute normalization, we note that at 13.8 GeV/c our data agree with those of Dzierba *et al.*[3] [for 14.2

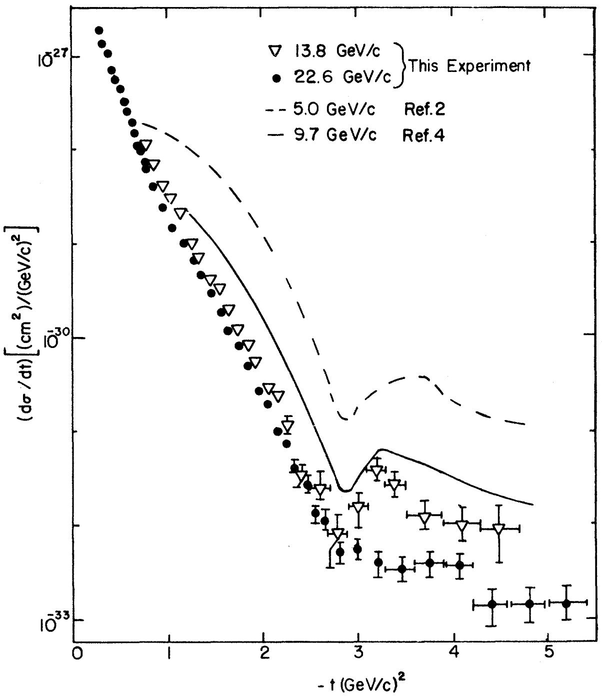

FIG. 3. Results of this experiment at 13.8 and 22.6 GeV/c together with curves through data of Ref. 2 at 5.0 GeV/c and Ref. 4 at 9.7 GeV/c.

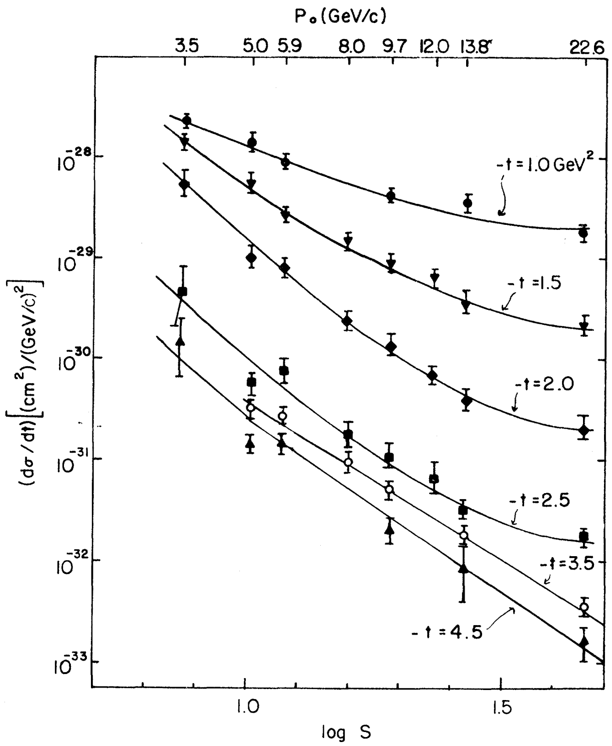

FIG. 4. Log$d\sigma/dt$ as a function of $\log_{10}s$ for several different values of t. Data at 3.5 GeV/c, Ref. 1; 5.0 GeV/c, Ref. 2; 5.9 and 9.7 GeV/c, Ref. 4; 8.0 and 12.0 GeV/c, Ref. 3; 13.8 and 22.6 GeV/c, this experiment. Interpolations have been made between data points where necessary, and in all cases quoted normalization errors have been added in quadrature with statistical errors. The curves are to guide the eye.

GeV/c, $|t| < 0.77$ (GeV/c)^2] and Owen *et al.*[4] [13.6 GeV/c, $1.2 < |t| < 2.3$ (GeV/c)^2]. Also at 22.6 GeV/c, our data for $|t| > 0.3$ (GeV/c)^2 together with the recent data of Foley *et al.*[9] for $|t| < 0.17$ (GeV/c)^2 at 22.1 GeV/c give a shape consistent with fits to $\pi^- p$ data in the 7–25-GeV/c range.[10]

In general, the present data show many of the features that were also present at lower momenta, and we can make a number of specific comparisons.

(1) At $-t \approx 1$ (GeV/c)^2, the differential cross section at both 13.8 and 22.6 GeV/c (the former when taken together with data from Ref. 8) changes slope from $\exp(8t)$ to $\exp(4.2t)$. At lower momenta, for example below 4 GeV/c,[1] this effect is an appreciable dip, but it becomes less marked with increasing momentum.

(2) In the region $2 < -t < 2.8$ (GeV/c)^2 the slope becomes steeper again, changing from $\exp(4.2t)$ to $\exp(5.2t)$.

(3) The dip at $-t = 2.8$ (GeV/c)^2 and subsequent rise, observed at lower momenta, is still present at 13.8 GeV/c. At 22.6 GeV/c it has largely gone away, becoming just an abrupt change in slope. However, within our statistics it is not possible to rule out a small or narrow dip.

(4) Within the momentum-transfer range covered by this experiment, the 22.6-GeV/c cross sections are all lower than those at 13.8 GeV/c for the same momentum transfers. This suggests that an asymptotic cross section has not been reached at 23 GeV/c. However, as seen in Fig. 4, where we show log$d\sigma/dt$ as a function of log$s$, the cross-section decrease with momentum is becoming less steep, at least for $|t| < 3$ (GeV/c)^2. Below $|t| = 3$ (GeV/c)^2, parametrizing the momentum dependence as $d\sigma/dt = A(t)s^{n(t)}$ as suggested by the Regge approach, we find $n = -3.5$ for incident momenta between 5 and 10 GeV/c, decreasing to $n = -1.5$ for 14 to 23 GeV/c. For $|t| > 3$ (GeV/c)^2 the expression $d\sigma/dt \propto s^{-3.5}$ seems to hold for the entire incident momentum region between 5 and 23 GeV/c.

It may be that an asymptotic cross section will be approached gradually, with the cross section being s independent up to some $|t|_{max}$, and $|t|_{max}$ increasing with increasing incident momentum. Certainly, for incident momenta up to 23 GeV/c, the simple Regge parametrization $s^{2\alpha(t)-2}$ does not fit the data in the region $1 < |t| < 3$ $(\mathrm{GeV}/c)^2$.

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Modified Golberger-Miyazawa-Oehme Sum Rule

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A modified form of the Goldberger-Miyazawa-Oehme sum rule is given in terms of experimental quantities at finite energy. It can be used either to test dispersion relations or to determine accurately and unambiguously the pion-nucleon coupling constant in terms of the πN scattering lengths.

Long ago, Goldberger, Miyazawa, and Oehme[1] (GMO) derived a sum rule which gives the s-wave πN scattering lengths in terms of the πN coupling constant and an integral involving the $\pi^\pm p$ total cross sections $\sigma^\pm$ over all energies. It was derived by assuming an unsubtracted dispersion relation for the crossing odd forward πN scattering amplitude $f_A(\omega) = \frac{1}{2}[f^+(\omega) - f^-(\omega)]$. The sum rule is

$$\mathrm{Re} f_A(\mu) = -\frac{2f^2}{\mu}\left(1 - \frac{\mu^2}{4M^2}\right)^{-1} + \frac{\mu^2}{4\pi^2}\int_\mu^\infty \frac{d\omega'}{q'}[\sigma^+(\omega') - \sigma^-(\omega')]. \tag{1}$$

There are three problems associated with Eq. (1): (a) The dispersion integral may not converge. (b) The dispersion integral may converge, yet the dispersion relation must be written in a subtracted form; we can always add a term linear in ω to the right-hand side of (1) without affecting its analytic property. (c) $\sigma^+ - \sigma^-$ must be known at all energies up to infinity.