ly improved by chopping the high-energy particles at a rate corresponding to the resonant frequency of the piezoelectric detector. It may be noted, however, that in many applications the particle beams are not chopped.

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[1]R. Hofstadter, to be published, and Stanford University, High Energy Physics Laboratory Report No. 599 (unpublished).

[2]The PZT disks were kindly supplied by Channel Industries, Santa Barbara, Calif. The catalog number of the disks is Channelite 5400.

[3]D. Miller, P. Schlosser, J. Burt, D. D. Glower, and J. M. McNeilly, IEEE Trans. Nucl. Sci. NS-14, 245 (1967).

[4]N. G. Einspruch, Solid State Phys. 17, 217 (1965).

[5]R. M. White, J. Appl. 34, 2123, 3559 (1963).

BACKWARD ELASTIC π^+p SCATTERING FROM 2.18 to 5.0 BeV/c*

J. P. Chandler,† R. R. Crittenden, K. F. Galloway, R. M. Heinz, H. A. Neal,‡ K. A. Potocki,§ W. F. Prickett,‖ and R. A. Sidwell
Indiana University, Bloomington, Indiana 47401
(Received 2 June 1969)

Differential cross sections for π^+p elastic scattering in the angular region $-0.6 \gtrsim \cos\theta_{\text{c.m.}} \gtrsim -0.98$ are presented for 13 incident pion momenta from 2.18 to 5.0 BeV/c. The striking features of the data are a backward peak at all momenta and a dip in the cross section at $u \approx -0.17$ for momenta between 2.75 and 5.0 BeV/c.

This Letter reports the results of an optical spark-chamber experiment performed at the Argonne National Laboratory zero-gradient sychrotron to measure the backward angular distribution of the cross section for π^+p elastic scattering. These cross sections, for 13 momenta from 2.18 to 5.0 BeV/c, result from 15 300 events recovered from 211 000 photographs. Pions scattered at laboratory angles between 70° and 150°, corresponding to $-0.6 \gtrsim \cos\theta_{\text{c.m.}} \gtrsim -0.98$, were studied. Thus our data cover $-0.7 \leqslant u \leqslant 0.1$ at 2.18 BeV/c and $-1.1 \leqslant u \leqslant 0$ at 5.0 BeV/c.[1]

The experimental layout is shown in Fig. 1. The external proton septum beam, with a momentum resolution of 1% full width at half-maximum and a central momentum uncertainty of less than 1%, struck a 12-in.-long liquid-hydrogen target. A gas threshold Čerenkov counter CG, not shown in Fig. 1, was used to separate pions from protons and kaons in the beam. At 2.18 BeV/c the beam intensity was 30 000 particles (15 000 pions) per burst, while at 5.0 BeV/c the intensity was 150 000 particles (40 000 pions) per burst.

A trigger of the system occurred when signals were detected from the beam counters (CG, B1, and B2), one of the proton counters (P1 or P2 in Fig. 1), and one of the six pion counters ($\pi1$-$\pi6$ in Fig. 1). A signal from the water Čerenkov counter was also required when either counter $\pi1$ or $\pi2$ detected a particle; this eliminated trig-

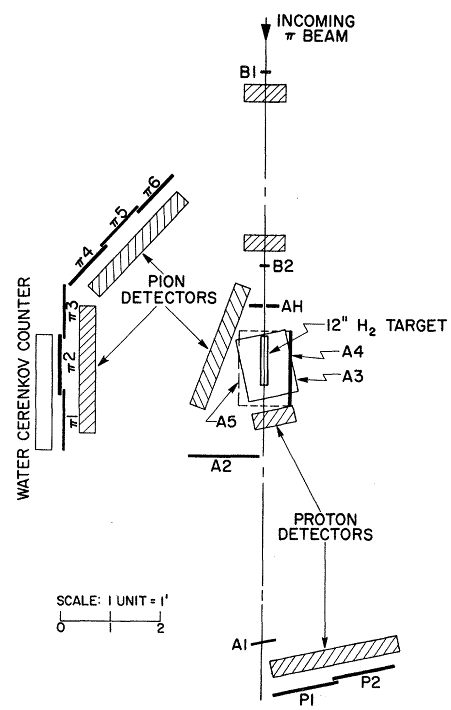

FIG. 1. The experimental layout.

gers from forward elastic scattering. An additional feature of the trigger was an array of six anticoincidence counters AH (which contained a 1-in.-diam hole for the beam) and A1-A5 (which covered essentially all of the solid angle not subtended by the detectors). Without them, the trigger rate would have increased by a factor of 11.

A set of seven, six-gap, optical spark chambers was used to record the paths of the incident beam, the scattered pion, and the recoil proton. The spark chambers are indicated in Fig. 1 by the hatched rectangles. The azimuthal acceptance was approximately 10%. The direct and stereo views of all chambers, together with fiducial lights, were recorded on a single 35-mm frame of film. The picture-taking rate varied from 0.3 per burst (at 5.0 BeV/c) to 0.8 per burst. The system was capable of recording one picture per burst. The overall magnification was about 1/50.

The data were recovered from the film by means of a cathode ray, flying spot, scanner digitizer (CRUDI) which was built at Indiana University.[2] This device was controlled by a CDC-3400 computer. The pictures were processed at a rate of 950 frames/h. A filter program removed spurious sparks from the digitized output and fitted three straight lines, constrained to intersect at a point, to those remaining. The standard deviation of sparks from the fitted lines was about 2 mm in real space.

We were able to use the redundancy of the spark-chamber arrangement to check the overall efficiency of the detection system, including the spark chambers and the measuring device, thus obviating the need for any manual measurement. This was done by determining the effect on the data of omitting chambers one at a time. The results indicated an overall detection efficiency of 98 ±2%.

A 3-standard-deviation cut on coplanarity was made on those events which passed the filter program, had vertices in the fiducial volume of the hydrogen target, and passed through the fiducial regions of the spark chambers and counters. The remaining events were placed in bins according to the proton angle. For each of these bins a histogram was made of the difference between the measured proton scattering angle and the proton scattering angle calculated from the measured pion angle, using elastic-scattering kinematics. Fig. 2 shows two of these histograms, with proton angles corresponding to $-0.95 \geq \cos\theta_{c.m.} > -0.975$ and $-0.7 \geq \cos\theta_{c.m.} > -0.725$, for 4.25 BeV/c. Background subtractions made from these plots determined the number of events in the prominent elastic peak; this subtraction ranged from 0% at low momenta near $\cos\theta_{c.m.} = -0.6$ to 40% at high momenta near $\cos\theta_{c.m.} = -0.98$.

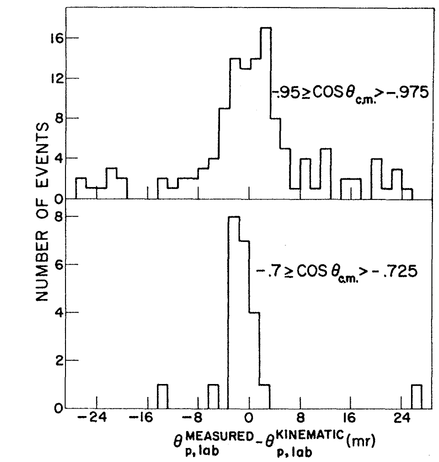

FIG. 2. The distribution of $\theta_{p\ \mathrm{lab}}^{\mathrm{meas}} - \theta_{p\ \mathrm{lab}}^{\mathrm{kin}}$ at 4.25 BeV/c for two bins of $\cos\theta_{p\ \mathrm{c.m.}}$ showing the variation in resolution and background for different experimental regions. Here $\theta_{p\ \mathrm{lab}}^{\mathrm{meas}} - \theta_{p\ \mathrm{lab}}^{\mathrm{kin}}$ is the difference between the measured proton lab angle and the proton lab angle found from the measured pion lab angle using elastic-scattering kinematics.

The data were corrected for the following effects: spark chamber and CRUDI inefficiency (2 ± 2%), counter inefficiency (1 ± 1%), beam attenuation in the hydrogen target (2%), nuclear interactions of the final-state particles (3 ± 1%), and lepton contamination in the beam (9 ± 6%). Our results, together with those of other experiments in this region,[3-5] are shown in Fig. 3, where we plot $d\sigma/du$ vs u. The error bars in Fig. 3 represent the statistical error.

The main features of the data at 2.75 BeV/c and higher momenta can be explained by Reggeized baryon exchange. The backward peak is a general characteristic of baryon exchange, while the dip in the cross section at $u \approx -0.17(\mathrm{BeV}/c)^2$ is caused by the wrong-signature nonsense zero in the N_α trajectory.[6,7] The theoretical cross section at 4.0 BeV/c based on the exchange of the N_α trajectory is shown as the dashed curve in Fig. 3.[8] No significant change in this prediction occurs when the Δ_δ trajectory is also included.[6,7] An application of the Veneziano model to this reaction shows that the effect of the N_γ trajectory is also small.[9]

At 2.18, 2.28, and 2.38 BeV/c, t-channel (meson) exchanges may become important at back-

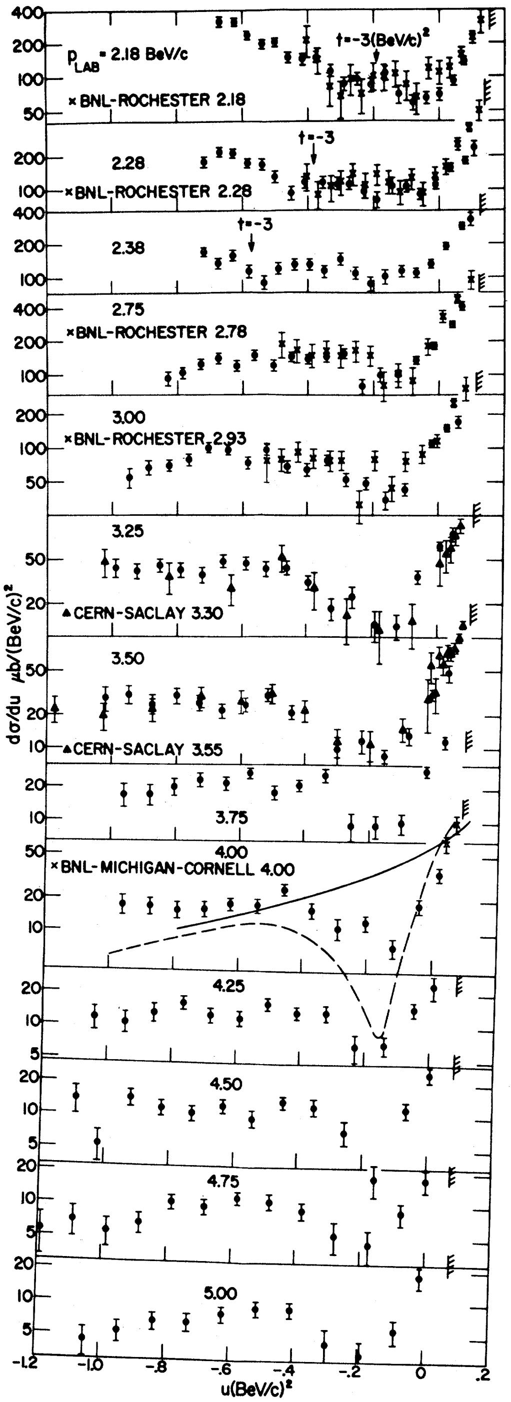

FIG. 3. Angular distributions for backward π^+p elastic scattering. The hatched region corresponds to unphysical values of u. The solid circles are data from this experiment; the Brookhaven National Laboratory–Rochester data are from Ref. 3, the CERN-Saclay data are from Ref. 4, and the Brookhaven National Laboratory–Michigan–Cornell data are from Ref. 5. Note that the ordinate is logarithmic. At 4.0 BeV/c, the dashed curve is from a Regge-pole calculation and the solid curve represents the cross section from s-channel resonances.

ward scattering angles. The $t=-3(\mathrm{BeV}/c)^2$ point, where a dip is expected in the t-channel amplitude,[10] is indicated in Fig. 3 for these lowest three momenta. The coexistence of t- and u-channel exchanges (and possibly s-channel resonances) precludes a simple theoretical interpretation at these momenta.

The solid curve at 4.0 BeV/c in Fig. 3 represents the cross section corresponding to the s-channel resonances lying on the Δ_δ trajectory.[11] According to duality,[12] these direct-channel resonances should adequately represent the amplitude, with the u-channel Regge-pole model an alternative and possibly less precise description.[13] Thus the marked disagreement between the 4.0-BeV/c solid curve and the data implies, in the duality picture, that other trajectories must be important in the s channel.[14]

The $u\approx-0.17(\mathrm{BeV}/c)^2$ dip in the cross section arises naturally in a Regge-cut model because of interference between the pole and cut terms.[15]

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†Present address: Physics Department, Florida State University, Tallahassee, Fla. 32306.

‡Alfred P. Sloan Foundation Fellow.

§Present address: 237 C Niblo Drive, Redstone Arsenal, Ala. 35808.

‖Present address: Physics Department, University of Manitoba, Winnipeg, Manitoba, Canada.

[1]s, t, u are the usual Mandelstam variables; see S. Mandelstam, Phys. Rev. 115, 1741 (1959).

[2]T. Carides, J. G. Cottingham, A. V. Feltman, A. S. Grossman, L. B. Leipuner, J. G. Marinuzzi, and G. G. Schwender, Rev. Sci. Instr. 38, 1425 (1967); K. A. Potocki, doctoral dissertation, Indiana University, 1968 (unpublished); W. F. Prickett, doctoral dissertation, Indiana University, 1968 (unpublished).

[3]A. S. Carroll, J. Fischer, A. Lundby, R. H. Phillips, C. L. Wang, F. Lobkowicz, A. C. Melissinos, Y. Nagashima, and S. Tewksbury, Phys. Rev. Letters 20, 607 (1968).

[4]J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, F. Plouin, W. F. Baker, P. J. Carlson, V. Cha-

baud, and A. Lundby, Nucl. Phys. B8, 31 (1968); W. F. Baker, P. J. Carlson, V. Chabaud, A. Lundby, J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, and F. Plouin, Phys. Letters 25B, 361 (1967); W. F. Baker, P. J. Carlson, V. Chabaud, A. Lundby, E. G. Michaelis, J. Banaigs, J. Berger, C. Bonnel, J. Duflo, L. Goldzahl, and F. Plouin, Phys. Letters 23, 605 (1966).

[5]J. Orear, R. Rubinstein, D. B. Scarl, D. H. White, A. D. Krisch, W. R. Frisken, A. L. Read, and H. Ruderman, Phys. Rev. 152, 1162 (1966).

[6]C. B. Chiu and J. D. Stack, Phys. Rev. 153, 1575 (1967).

[7]V. Barger and D. Cline, Phys. Rev. Letters 21, 392 (1968), and 19, 1504 (1967).

[8]The curve is from Ref. 6 and does not result from a fit to our data, which presumably could improve the agreement between the theoretical curve and the data.

[9]K. Igi, Phys. Letters 28B, 330 (1968).

[10]N. E. Booth, Phys. Rev. Letters 21, 465 (1968).

[11]V. Barger and D. Cline, Phys. Rev. 155, 1792 (1967).

[12]R. Dolen, D. Horn, and C. Schmid, Phys. Rev. 166, 1768 (1968); C. Schmid, Phys. Rev. Letters 20, 689 (1968).

[13]The u-channel exchange amplitude may only contain a semilocal average of the effects of s-channel resonances.

[14]This possibility is under investigation: R. Crittenden, R. Heinz, D. Lichtenberg, and E. Predazzi, to be published.

[15]F. Henyey, G. L. Kane, J. Pumplin, and M. H. Ross, Phys. Rev. (to be published).

DIFFERENTIAL CROSS SECTION AND POLARIZATION IN THE REACTION $\pi^+ + p \to K^+ + \Sigma^+$ FROM 3 to 7 GeV/c*

S. M. Pruss, C. W. Akerlof, D. I. Meyer, and S. P. Ying
Harrison M. Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48104

and

J. Lales, R. A. Lundy, D. R. Rust, C. E. W. Ward, and D. D. Yovanovitch
Argonne National Laboratory, Argonne, Illinois 60439
(Received 11 April 1969; revised manuscript received 16 June 1969)

We have measured the differential cross section and polarization for the reaction $\pi^+ + p \to K^+ + \Sigma^+$ for K laboratory angles between 3° and 17°. The reaction is dominated by a large forward peak which shrinks rapidly and decreases slowly in size with increasing energy. A break in this exponential occurs at $-t = 0.4$ (GeV/c)^2 beyond which the cross section falls much more slowly. The polarization is small for values of $-t$ less than 0.3 beyond which it becomes large and positive and remains positive to the largest angles measured. It is independent of energy within experimental errors.

The reaction $\pi^+ + p \to K^+ + \Sigma^+$ is of interest because according to present ideas it should be dominated by the exchange of the strange counterparts of the ρ and A_2 trajectories. We report here a measurement of $d\sigma/dt$ and polarization from 3° to 17° in the laboratory frame based on 40 000 events which greatly increases the knowledge of the reaction.

The apparatus is shown in Fig. 1. It consists of wire spark chambers before and after a magnet to measure the K^+ momentum and angle. The Cherenkov counter C is placed in anticoincidence to reject π^+ mesons. The solid-angle acceptance of the experiment was defined by a counter just upstream from the bending magnet. In addition a set of wire chambers detected the proton from the decay $\Sigma^+ \to p + \pi^0$. From the K^+ momentum and angle the missing mass could be calculated. An additional kinematic restriction could be applied by requiring a track in the kinematically allowed region for a proton from the Σ^+ decay. The spark chamber data was read out and calculated on line with an ASI-6020 computer.

During the experiment elastic $\pi^+ + p$ scattering runs were interspersed with $K^+ + \Sigma^+$ runs by removing the Cherenkov anticoincidence require-

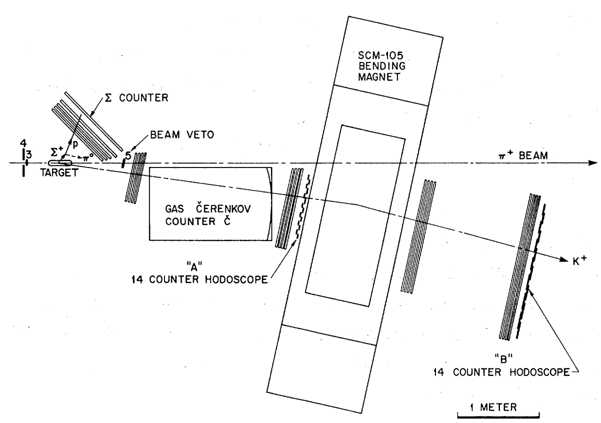

FIG. 1. A plan view of the experimental apparatus.