J. Benecke *et al.*, Phys. Rev. 188, 2159 (1969).
[6]G. Belletini *et al.*, Nucl. Phys. 79, 609 (1966).
[7]T. H. Burnett *et al.*, Phys. Rev. Lett. 30, 937 (1973); C. A. Ayre *et al.*, in *Proceedings of the Thirteenth International Cosmic Ray Conference, Denver, 1973* (University of Colorado, Denver, Colo., 1973); L. Leipuner *et al.*, in *Proceedings of the Thirteenth International Cosmic Ray Conference, Denver, 1973* (University of Colorado, Denver, Colo., 1973), and private communication.

Energy Dependence of the Double-Charge-Exchange Reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$†

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In an experiment at the Argonne National Laboratory zero-gradient synchrotron we have determined the forward differential cross sections for the double-charge-exchange reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$ for incident beam momenta up to 5 GeV/c. The production angle and momentum of the forward-going positive particle (π^+ or K^+) were measured with a high-resolution focusing wire-spark-chamber spectrometer and the two-body final states were selected by the missing-mass technique.

Our current understanding of high-energy hadron collisions is based on the idea that particle exchange provides the dominant force for interactions above a few GeV/c incident momentum. In time, the theoretical or phenomenological models which have embodied this primitive notion have grown steadily more ornate to allow greater freedom in fitting the expanding experimental data. Consequently, these models have become less testable by direct experiment and there have been no new guides to lead our physical intuition.

As a partial solution to this problem we have continued an earlier study[1] of the double-charge-exchange (DCX) reactions $\pi^- p \to K^+\Sigma^-$, $K^- p \to \pi^+\Sigma^-$, and $K^- p \to K^+\Xi^-$. The significance of these three reactions is that none of them can take place by the single exchange of any singly charged particle. Thus in the absence of normally large exchange forces we have a sensitive test for the existence of any of the three possible competing processes: (1) double particle exchange, (2) exotic single particle exchange, (3) intermediate s-channel resonance formation. In addition, by examining the energy behavior of the DCX cross sections we can hope to identify the dominant contribution in the asymptotically high-energy regime. This has been expected to be the double-particle-exchange diagrams which would yield differential cross sections with an $s^{-2.5}$ to s^{-3} behavior.[2]

The three reactions listed above also have some common properties which should set further limits on viable theoretical descriptions. For example, $\pi^- p \to K^+\Sigma^-$ and $K^- p \to \pi^+\Sigma^-$ are related by line crossing, so that these cross sections should be identical if induced by single exotic exchange and at least similar if induced by double particle exchange. $K^- p \to \pi^+\Sigma^-$ and $K^- p \to K^+\Xi^-$ have the same quantum numbers in the s channel, so that energy-dependent structure due to Y^* resonances should be expected in both reactions for the same incident momenta.

From our previous work we had experience with the experimental difficulties which beset measurements of the DCX reactions. Since the cross sections are all very small, an intense beam of incident particles is required on the hydrogen target. With available π/K ratios of the order of 200, the largest number of events could be obtained for the reaction $\pi^- p \to K^+\Sigma^-$, so that the experimental design concentrated on the detection of this particular channel. This required that a final-state K^+ be identified against an overwhelming background of pions and protons. At 5 GeV/c, for every K^+ from the reaction $\pi^- p \to K^+\Sigma^-$ there were 1000 π^+ and 200 protons within the missing-mass resolution of the experimental apparatus. To obtain sufficient rejection ratios against competing particle species, four Cherenkov counters were constructed to identify the positive particle in the final state. An unavoidable consequence was that the mass of the Cherenkov radiator to count kaons also produced substantial Coulomb scattering of the detected particle. Finally, since the cross section for the reaction $\pi^- p \to K^+\Lambda^0\pi^-$ rises steeply at the $\Lambda^0\pi^-$ threshold, high resolution was required to separate the Σ^- missing-mass peak from the onset of the $\Lambda^0\pi^-$ continuum which is 58 MeV higher.

A high-intensity negative beam was created in an internal target inside the vacuum chamber of the Argonne zero-gradient synchrotron. This beam was momentum dispersed through a 20° bend, focused onto a momentum-defining hodoscope of ten scintillation counters, and then transported through a second stage to a final focus on a 24-in.-long hydrogen target. The mass of the beam particle was tagged with four Cherenkov counters: one to count kaons and three to count pions. Two hodoscopes of five counters each tagged the horizontal and vertical divergence of the beam 5 m upstream from the hydrogen target.

The positive particles emitted in the forward direction were detected in a focusing quadrupole spectrometer consisting of five magnetic elements. The first of these following the hydrogen target was a 36-in.-long bending magnet to steer the positive particles created in the target away from the negative beam. Three quadrupoles were arranged to bring the particles from within a 2.5-msr solid angle into an approximately parallel bundle at the final quadrupole exit. This allowed a 2-m-long drift space on each side of a 72-in.-long momentum-analyzing magnet without further reduction of the subtended solid angle.

Four sets of wire spark chambers determined the bend angle through the analyzing magnet; the drift region between chambers was kept low in mass to reduce multiple Coulomb scattering. In particular this dictated the placement of the spectrometer Cherenkov counters upstream of the first wire spark chamber. The electronic trigger was arranged to fire on either a π^- in the incident beam yielding a K^+ or a K^-, or a $\bar{p}$ yielding any positive particle in the spectrometer. After every five beam spills the trigger was altered under computer control to include incident π^- yielding final-state protons. This permitted the simultaneous acquisition of π^-p backward-scattering data which continuously monitored the experimental apparatus.

Data were taken for eleven different values of incident momentum from 1.90 to 5.00 GeV/c. At each momentum the π^-p backward elastic missing-mass peak checked the spectrometer dispersion and resolution. Analysis for every reaction channel was performed identically. First, the three beam hodoscopes were checked for uniqueness. If more than one counter in any of the three arrays fired the event was ignored. Data from the wire spark chambers were used to construct a trajectory through the analyzing magnet and to determine the particle momentum. This trajectory was then traced back through the three quadrupoles and steering magnet to find the original momentum three-vector. With the tagged Cherenkov-counter data to identify the beam and spectrometer particle masses, the missing mass was computed. Even at the highest momentum of 5 GeV/c the Σ^- peak was clearly resolved from the $\Lambda^0\pi^-$ threshold. The inelastic background behaved like a step function at threshold with the observed shape dominated by the experimental missing-mass resolution. The number of events within the Σ^- peak was determined by fitting the shape of the missing-mass distribution with the sum of a Gaussian signal and a background function consisting of a constant plus an error-function integral centered at the $\Lambda^0\pi^-$ threshold. All of the nonlinear parameters for these distributions were independently determined from the π^- mass peak from π^-p backward elastic scattering so that the fits to the DCX data required a minimal number of free parameters. With this procedure the fitted number of events in the Σ^- peak was quite stable under a variety of modifications of the background function.

The differential cross sections were corrected for beam muon contamination, hodoscope losses, wire–spark-chamber inefficiencies, and particle absorption and decay. The results are plotted in Figs. 1 and 2. Because the systematic errors vary slowly, the uncertainty in the energy dependence should be dominated by statistical errors only. Furthermore, the data for different momenta were interlaced in time so that no long-term experimental drifts could seriously affect the energy behavior.

For reasons indicated earlier, the best statistics were obtained for the $\pi^-p \to K^+\Sigma^-$ channel. From Fig. 1(a) it is apparent that the energy dependence of this differential cross section changes markedly for incident momenta above 3 GeV/c. Below this point the cross section drops very rapidly with a power-law behavior of $s^{-9.6}$. In the region above 3 GeV/c the magnitude of the slope sharply decreases so that between 4 and 5 GeV/c the cross section behaves like $s^{-1.1}$ with a statistical error of ± 0.8 in the exponent. This remarkable change in energy dependence is inconsistent with the Regge-cut descriptions which asymptotically expect a more rapid decrease, like s^{-3}, at high energy.[2] Equally significant is the magni-

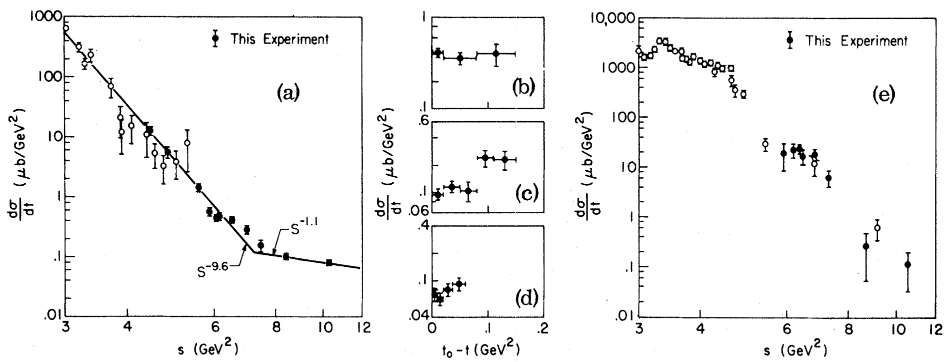

FIG. 1. (a) Energy dependence of the $\pi^- p \rightarrow K^+ \Sigma^-$ differential cross section at zero degrees averaged over the angular acceptance of the spectrometer. This corresponds to an average t' value of 0.02 $(\mathrm{GeV}/c)^2$ at 5.0 GeV/c and proportionally smaller at lower momenta. Other data from Ref. 3. (b)–(d) Angular distributions for $\pi^- p \rightarrow K^+ \Sigma^-$ at 3.0, 4.0, and 5.0 GeV/c, respectively. (e) Energy dependence of the $K^- p \rightarrow \pi^+ \Sigma^-$ differential cross section at zero degrees. Other data from Ref. 4.

tude of the DCX cross section which is some 5000 times smaller than the comparable single-exchange reaction $\pi^+ p \rightarrow K^+ \Sigma^+$ at 5 GeV/c. Regge-cut models which require large cut amplitudes to fit the single-exchange processes find difficulty in reconciling these small DCX results.

Some information about the angular distribution of the $\pi^- p \rightarrow K^+ \Sigma^-$ channel was obtained at 3 and 4 GeV/c by increasing the current in the spectrometer steering magnet. Geometry restricted the maximum momentum transfer to 0.15 $(\mathrm{GeV}/c)^2$; the differential cross sections are plotted in Figs. 1(b)–1(d) for 3, 4, and 5 GeV/c, respectively. There is a forward dip structure at 4 GeV/c which is probably also present at 5 GeV/c. Unfortunately, we do not cover large enough momentum transfers to make any definitive comparisons with the cut models.

The precipitous decrease of the $\pi^- p \rightarrow K^+ \Sigma^-$ cross section from 1.5 to 3.0 GeV/c is matched by similar behavior in the line-crossed reaction $K^- p \rightarrow \pi^+ \Sigma^-$ [see Fig. 1(e)]. This s^{-10} characteristic dependence has been noted previously for exotic exchange reactions such as $K^- p \rightarrow p K^-$[6] and $\bar{p}p \rightarrow \bar{p}p$,[7] as well as for the lower-energy data for reactions such as $\pi^- p \rightarrow \varphi n$.[8] The prevalence of this effect in so many different channels suggests that the low-energy cross sections are dominated by s-channel resonances which decouple above a few GeV/c. This is corroborated by the comparison of the $K^- p \rightarrow \pi^+ \Sigma^-$ and $\pi^- p \rightarrow K^+ \Sigma^-$ reactions at 3 GeV/c, where the $K^- p \rightarrow \pi^+ \Sigma^-$ cross section is 43 times larger, which is difficult to reconcile with any single- or double-exchange mechanism. The evidence of structure in the K^--induced reaction at 3 GeV/c also confirms the idea that this channel maintains resonant forces to somewhat higher energies than the $\pi^- p$ system.

After a suggestion of Frautschi,[9] we have examined the possibility of fitting the energy behavior of the DCX data with the statistical model. This model is consistent with the rapid decrease of the cross sections at low energy but cannot account for the large difference in magnitude between $\pi^- p \rightarrow K^+ \Sigma^-$ and $K^- p \rightarrow \pi^+ \Sigma^-$. Moreover, the apparent onset of exchange forces above 3 GeV/c restricts the testability of this theory to a narrow range in energy.

Cross sections for $K^- p \rightarrow K^+ \Xi^-$ are shown in Fig. 2. Although the data are much poorer statistically, they show that the cross sections for $K^- p \rightarrow K^+ \Xi^-$ and $\pi^- p \rightarrow K^+ \Sigma^-$ are similar in magnitude

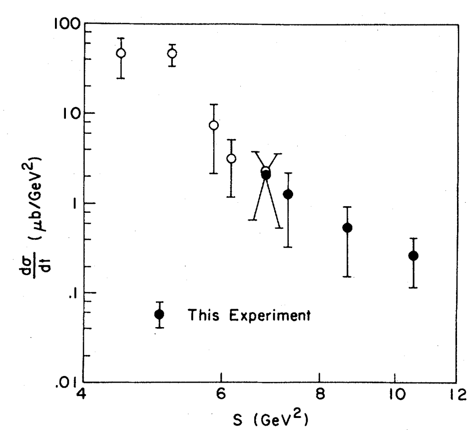

FIG. 2. Energy dependence of the $K^- p \rightarrow K^+ \Xi^-$ differential cross section at zero degrees. Other data from Ref. 5.

out to 4 GeV/c or so. Note also that at around 5 GeV/c the $\pi^- p \to K^+\Sigma^-$ and $K^- p \to \pi^+\Sigma^-$ cross sections are approximately equal, suggesting that exchange forces dominate at this energy. If the $s^{-1.1}$ behavior of the $\pi^- p \to K^+\Sigma^-$ channel remains true above 5 GeV/c, we may be required to consider the exchange of four or more quarks as a force not intrinsically different from the exchange of a ρ or K^*, only considerably weaker in amplitude.

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[1]C. W. Akerlof *et al.*, Phys. Rev. Lett. 27, 539 (1971).

[2]R. J. N. Phillips, Phys. Lett. 24B, 342 (1967); N. W. Dean, Nucl. Phys. B7, 311 (1968); C. Michael, Phys. Lett. 29B, 230 (1969); M. Ross, F. S. Henyey, and G. L. Kane, Nucl. Phys. B23, 269 (1970); C. Quigg, Nucl. Phys. B34, 77 (1971).

[3]$\pi^- p \to K^+\Sigma^-$ data references: O. I. Dahl *et al.*, Phys. Rev. 163, 1430 (1967); M. L. Good and R. R. Kofler, Phys. Rev. 183, 1142 (1969); O. Goussu *et al.*, Nuovo Cimento 42A, 606 (1966).

[4]$K^- p \to \pi^+\Sigma$ data references: Amsterdam-Nijmegen Collaboration, in Proceedings of the Second Aix en Provence International Conference on Elementary Particles, Aix en Provence, France, September, 1973 (unpublished), Contributed Paper No. 225; J. Badier *et al.*, Commissariat à l'Energie Atomique, Saclay, Report No. CEA-R3037, 1966 (unpublished); A. Berthon *et al.*, Nucl. Phys. B24, 417 (1970); P. M. Dauber *et al.*, Phys. Lett. 23, 154 (1966); D. F. Kane, Jr., Phys. Rev. D 5, 1583 (1972); G. W. London *et al.*, Phys. Rev. 143, 1034 (1966).

[5]$K^- p \to K^+\Xi^-$ data references: Badier *et al.*, Ref. 4; P. M. Dauber *et al.*, Phys. Rev. 179, 1262 (1969).

[6]A. S. Carroll *et al.*, Phys. Rev. Lett. 23, 887 (1969); C. A. Smith, thesis, University of Rochester (unpublished); V. Chabaud *et al.*, Phys. Lett. 38B, 445 (1972), and CERN NP Internal Report No. 72-12 (unpublished); A. Eide *et al.*, Nucl. Phys. B60, 173 (1973).

[7]W. W. M. Allison *et al.*, Nucl. Phys. B56, 1 (1973); V. Chabaud *et al.*, Phys. Lett. 38B, 449 (1972), and CERN NP Internal Report No. 72-12 (unpublished); W. A. Cooper *et al.*, Nucl. Phys. B16, 155 (1970); Eide *et al.*, Ref. 6; W. M. Katz *et al.*, Phys. Rev. Lett. 19, 265 (1967); G. R. Lynch *et al.*, Phys. Rev. 131, 1276 (1963); J. Lys, Phys. Rev. Lett. 21, 1116 (1968); D. L. Parker *et al.*, Nucl. Phys. B32, 29 (1971); J. K. Yoh *et al.*, Phys. Rev. Lett. 23, 506 (1966).

[8]D. Bollini *et al.*, Nuovo Cimento 60A, 543 (1969); J. H. Boyd *et al.*, Phys. Rev. 166, 1458 (1968); O. I. Dahl *et al.*, Phys. Rev. 163, 1377 (1967); R. Diebold, private communication; B. D. Hyams *et al.*, Nucl. Phys. B22, 189 (1970); H. H. Williams, Ph.D. thesis, Stanford University, 1972 (unpublished).

[9]S. Frautschi, Nuovo Cimento 12A, 134 (1972), and private communication.

ERRATUM

NEW MEASUREMENT OF THE Σ^- MAGNETIC MOMENT. B. L. Roberts, C. R. Cox, M. Eckhause, J. R. Kane, R. E. Welsh, D. A. Jenkins, W. C. Lam, P. D. Barnes, R. A. Eisenstein, J. Miller, R. B. Sutton, A. R. Kunselman, R. J. Powers, and J. D. Fox [Phys. Rev. Lett. 32, 1265 (1974)].

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