Measurement of the Double-Charge-Exchange Reactions $\pi^-p \to K^+\Sigma^-$ and $K^-p \to \pi^+\Sigma^-$†

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The forward cross sections for the reactions $\pi^-p \to K^+\Sigma^-$ and $K^-p \to \pi^+\Sigma^-$ have been determined for incident particle momenta in the range of 2.75 to 3.50 GeV/c, and an upper limit was established at 5.00 GeV/c. These measurements show that the double-charge-exchange process $\pi^-p \to K^+\Sigma^-$ is suppressed by a factor of 1500 at 3 GeV/c relative to the single-exchange reaction $\pi^+p \to K^+\Sigma^+$.

Recently there has been a surge of interest in two-body reactions in which the interaction appears to take place by the exchange of two units of electrical charge.[1] This interest has been sparked by the lack of evidence for "exotic" particles belonging to higher multiplicity representations of SU(3) and the peripherality of two-body reactions above 3 GeV/c. In addition, if the exchange of two or more particles in the same collision is suppressed, one expects that the cross sections for reactions such as $\pi^-p \to K^+\Sigma^-$ in the forward direction and K^-p backward elastic scattering will be small. If the experimental data bear out this expectation, one can conclude that exotic mesons, s-channel resonances, and double Reggeon exchange are all unimportant. On the other hand, if double-charge-exchange (DCE) reactions occur with appreciable cross sections, one or more of the above three processes may be significant although the determination of which one(s) will not be easy.

In the past few years there have been several reports[2-8] of evidence for large DCE cross sections, and there have been an almost equal number of papers[9-12] refuting these claims. One concludes that it is very difficult to determine the DCE contributions in quasi two-body reactions such as $\pi^-p \to \pi^+\Delta^-$ or $pn \to \Delta^-\Delta^{++}$. To avoid these difficulties, we chose to study the two-body reactions

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

$$K^-p \to \pi^+\Sigma^-. \tag{2}$$

If double-particle exchange is important, Reactions (1) and (2), which exchange two mesons, will have larger cross sections than K^-p backward elastic scattering which must exchange both a meson and a baryon. In other words, the Regge-cut contributions are expected to be larger for the reactions which exchange only mesons. Thus, one of the principal aims of this experiment was to provide a measure of the upper limit of Regge-cut amplitudes where they could be expected to be large. Since the available π^- flux was approximately 100 times more intense than the K^- flux most of the effort of this experiment was spent in measuring Reaction (1). However some data for Reaction (2) were collected simultaneously and will be presented as well.

The layout for the experimental apparatus is shown in Fig. 1 of an earlier paper.[13] The incident π^-, K^- beam was created in one of the external proton beams from the zero-gradient synchrotron at the Argonne National Laboratory. This beam was momentum analyzed, and the π^- were electronically tagged with two Cherenkov counters $CPI1$ and $CPI2$ prior to being focused on a 24-in.-long liquid-hydrogen target. Following the target, a 30-in. steering magnet diverted the negative beam 5° to the right while any positively charged particles created were bent into the spectrometer. This magnetic separation of charge species allowed low counting rates in the spectrometer in the presence of high incident beam intensities.

The mass of the positive particles was determined by three focusing gas threshold Cherenkov counters labeled $C1$, $C2$, and $C4$. $C1$ was a high-pressure counter designed to count kaons, and $C2$ and $C4$ were low-pressure counters to detect pions. The particle momentum was determined by four sets of wire spark chambers placed on both sides of a large bending magnet. All the data from the wire spark chambers and hodoscopes and the pulse height from Cherenkov counter $C1$ were buffered to an EMR 6040 computer which analyzed the missing mass of each event, monitored the performance of the apparatus, and logged the data on magnetic tape for later reanalysis.

The event trigger was formed by the coincidence of several sets of scintillation counters in the beam and the spectrometer ($BM1$, $BM2$, $BM3$, $K1$–4, KM, KR) and the Cherenkov counter

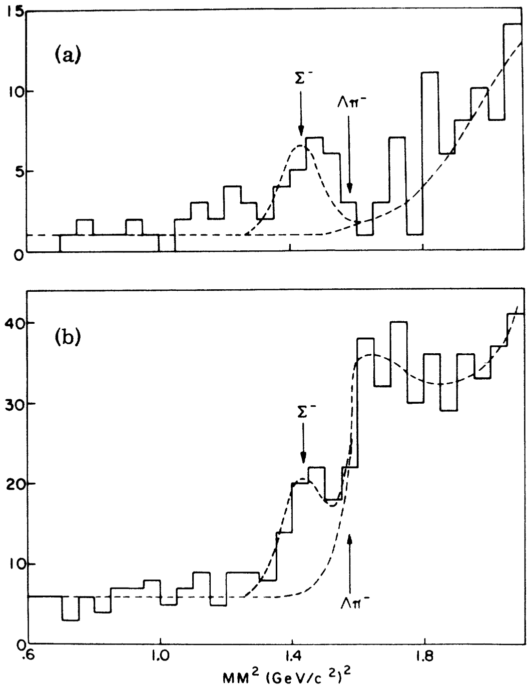

FIG. 1. (a) Spectrum of missing-mass squared for $\pi^-p\to K^+\Sigma^-$ at 2.75 GeV/c for events with $C1$ pulse height greater than 12. (b) Spectrum of missing-mass squared for $\pi^-p\to K^+\Sigma^-$ at 2.75 GeV/c with $C1$ pulse height greater than zero. The dashed lines indicate the results of the least-squares fits for the background and the Σ^- peak.

logic. The Cherenkov counter logic was designed to simultaneously accumulate data for the reactions $\pi^-p\to K^+\Sigma^-$, $K^-p\to\pi^+\Sigma^-$, and $K^-p\to K^+\Xi^-$ and reject the copious flux of protons and π^+.[14] Sorting of the particle masses for each event was accomplished by the computer using the tagging information stored in fast latches from each of the Cherenkov counters.

The magnetic fields in the steering and analyzing magnets were carefully determined by measuring the trajectories of beam particles deflected through the entire system. The missing-mass resolution was established in a previous part of this experiment which investigated the reaction $\pi^+p\to K^+\Sigma^+$ and has been reported previously.[13]

During the course of the experiment it became clear that the cross section for $\pi^-p\to K^+\Sigma^-$ was much lower than anticipated and much smaller than the reaction $\pi^-p\to K^+\pi^-\Lambda^0$. The three-body inelastic cross section rises extremely rapidly at threshold for essentially kinematic reasons, and so with finite missing-mass resolution the Σ^- missing-mass peak was almost obscured in the tail of the inelastic spectrum [see Fig. 1(b)]. Fortunately the pulse-height information from the kaon Cherenkov counter $C1$ allowed some discrimination against the slower kaons associated with the inelastic reactions. By raising the lower limits on the acceptable pulse height from $C1$, the Σ^- signal was enhanced to a convincing level. The effect of this pulse-height cut on the missing-mass spectrum is shown in Fig. 1(a).

In order to provide a quantitative basis for this analysis the pulse-height spectra of the $C1$ counter were measured for electronically defined K^- beams of the appropriate momenta. This permitted a direct determination of the detection efficiency for any pulse-height cut later chosen. In addition we took several runs to measure the missing-mass spectrum for the inelastic reaction $\pi^-p\to\pi^+X^-$. These data were used to determine experimentally the shape of the inelastic tail leaking under the Σ mass peak.

The cross sections for the DCE reactions were extracted by a least-squares fitting of background plus Σ^- peak to the missing-mass spectra. The background was assumed to be constant below the three-body inelastic threshold and to behave like a Fermi distribution function near threshold with a characteristic shape determined by the $\pi^-p\to\pi^+X^-$ data. The experimental width of the Σ^- peak was set equal to the width observed in the allowed reaction $\pi^+p\to K^+\Sigma^+$. These choices made the fitting procedure less arbitrary than if only the DCE data had been used. Checks of the sensitivity of the method showed that systematic errors due to choice of parameters were approximately the same as the statistical errors of the fits.

The extracted differential cross sections for $\pi^-p\to K^+\Sigma^-$ and $K^-p\to\pi^+\Sigma^-$ are shown in Figs. 2(a) and 2(b), respectively, plotted as functions of s. The error bars indicated represent the statistical error determined from the least-squares analysis plus an estimate of the systematic fitting error. The differential cross sections are averaged over a solid angle of 2 msr around a zero-degree production angle. This solid-angle bite was so small that no structure could be detected in the angular distributions. In addition to the data from this experiment, Fig. 2 shows the data from several bubble-chamber experiments,[16,17] mostly at lower momenta.

The salient feature of the data shown in Fig. 2 is the rapid decrease of the forward differential cross section as a function of s. This behavior has been noted previously[18] in the case of the backward scattering reaction $K^-p\to pK^-$ whose

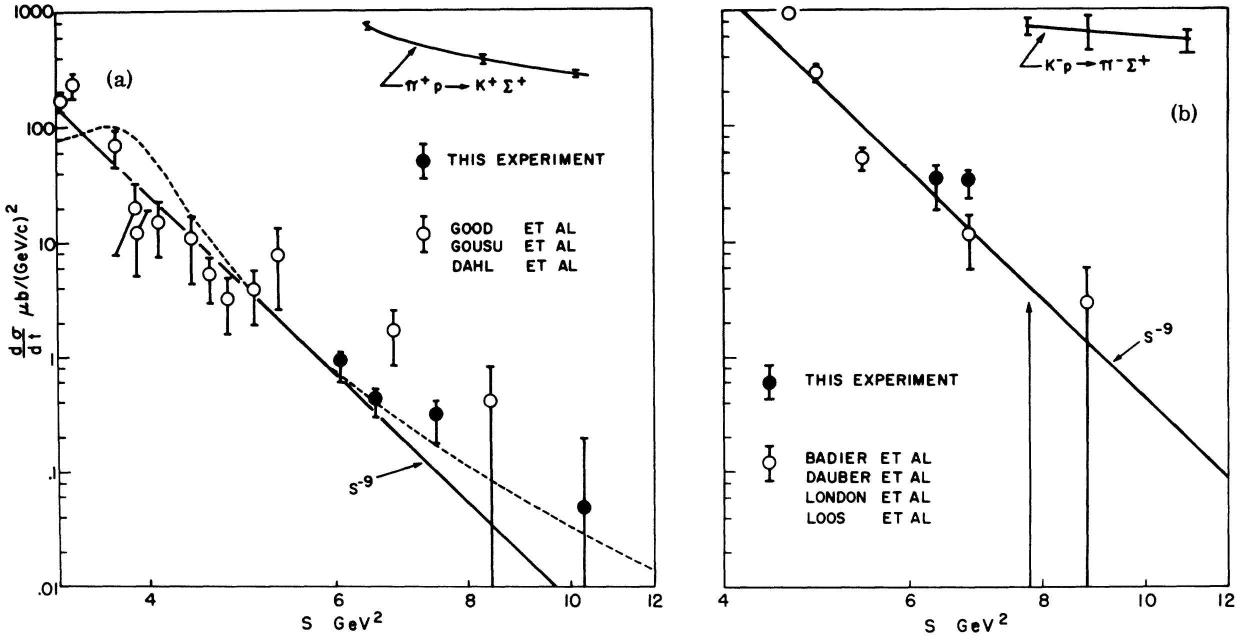

FIG. 2. (a) The differential cross section at zero degrees for $\pi^-p\rightarrow K^+\Sigma^-$ as a function of s. The dashed line is the contribution of the $\Delta(1950)$ decay as determined from the parameters of Kalmus *et al.* (Ref. 15). (b) The differential cross section at zero degrees for $K^-p\rightarrow\pi^+\Sigma^-$ as a function of s.

cross section exhibits an s^{-9} dependence for K^- momenta in the range of 2 to 5 GeV/c. Thus in Fig. 2 we have also drawn straight lines with an s^{-9} slope for comparison. For the reaction $\pi^-p\rightarrow K^+\Sigma^-$ this extremely rapid decrease is followed as the cross section drops by at least $2\frac{1}{2}$ orders of magnitude.

We also wished to compare these data with some estimate of the effects of s-channel resonances. The only reliable branching ratio for high-mass N^* resonances to $K\Sigma$ final states is from the data of Kalmus, Borreani, and Louie[15] for the $\Delta(1950)$. Using these branching ratios, a simple Breit-Wigner resonance shape, and isospin Clebsch-Gordan coefficients we obtained the dashed curve in Fig. 2(a). It is remarkable that this curve, with no adjustable parameters, fits the data so well. This agreement which is perhaps fortuitous should indicate the difficulty in comparing this or similar experiments with theoretical calculations which only consider exchange forces. The point is simply that the entire observed cross section may be due to the tails of s-channel resonances whose contribution is difficult to estimate.

In the region of 3 GeV/c the cross section for $K^-p\rightarrow\pi^+\Sigma^-$ is about 50 times greater than for $\pi^-p\rightarrow K^+\Sigma^-$. These reactions are related by crossing of initial and final mesons so it is not easy to obtain significantly different cross sections for these reactions from a theoretical model which considers only exchange processes.[19,20] The most plausible explanation for this effect is the presence of stronger s-channel resonances in the K^-p initial state. This view is supported by the observation that the largest DCE cross sections have been measured for $\bar{p}p$ reactions such as $\bar{p}p\rightarrow p\bar{p}$ (backward elastic) and $\bar{p}p\rightarrow\overline{\Sigma}^-\Sigma^-$. Even at high energies the major part of the $\bar{p}p$ total cross section leads to annihilation of the initial baryons, a process which must occur predominantly via s-channel forces. Thus we find a rough correlation between the magnitude of DCE cross sections and strength of s-channel intermediate states.

It should also be noted that the cross section for $\pi^-p\rightarrow K^+\Sigma^-$ is approximately 1500 times smaller than for the allowed reaction $\pi^+p\rightarrow K^+\Sigma^+$. A similar result was obtained by Abramovich *et al.*[21] for the ratio of double to single exchange by comparing $\pi^-p\rightarrow K^0\Sigma^0$ with $\pi^+p\rightarrow K^+\Sigma^+$ at 3.9 GeV/c. This suppression requires that the Regge-cut models which attempt to fit these data must contain delicate cancelations of large amplitudes.[19] In any case the ratio of these cross sections indicates the overall insignificance of high-mass s-channel resonances in the πp system and a lack of evidence for $I=\frac{3}{2}$, $S=1$ exotic mesons.

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Parity-Nonconserving One-Pion-Exchange Potential*

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It is argued that the strangeness-conserving weak currents *can* contribute to the single-pion–exchange parity-nonconserving potential between nucleons bound in nuclei. Although this contribution is reduced by $V_{\text{nuclear}}/M \sim 0.04$, it may be comparable in strength with that usually calculated. Estimates of the strength of an off-mass-shell $NN\pi$ vertex are carried out; neutral pion emission can occur. It is shown that the $\Delta(1236)N\pi$ weak vertex can be neglected.

The one-pion–exchange parity-nonconserving (PN) potential between nucleons has been calculated in the past[1] by means of current algebra and the use of theories of weak interactions. It was first shown by Barton,[2] on the assumption of *CP* invariance of the weak Hamiltonian, that there can be no contribution to the single pseudoscalar meson (π, η^0) exchange force from the strangeness-conserving weak current.[3] (Although this argument assumes only first-class currents, the evidence[4] for second-class currents in nuclei is still sufficiently weak that we also neglect them in the following.) In the Cabibbo theory of the weak interactions, which we take as our framework, the one-pion–exchange PN force[3] is thus only due to the strangeness-changing currents and is reduced in strength relative to other exchanges[3] by $\tan^2\theta \approx 0.05$, where θ is the Cabibbo angle. The force is effective despite this reduction because of its long range.

The *CP* arguments which predict the vanishing of the $\cos^2\theta$ contribution assume that the initial and final nucleons are free ones. Indeed, an effective weak Hamiltonian density such as[2]

$$\mathcal{H}_{\text{eff}}{}^{\text{PN}} = g_1 \bar{\psi}\, \gamma^\mu \vec{\tau} \cdot \psi \nabla_\mu \vec{\varphi} \qquad (1)$$

vanishes for the nucleons on their mass shell; however, in general, the matrix element of this Hamiltonian is proportional to the extent that the two baryons (fields $\bar{\psi}$, ψ) are off their mass shell. To date, all parity-nonconserving experiments have been carried out in nuclei. In such experiments the nucleons are off their mass shell by $\sim V/M$, where V is a nuclear potential and M the nucleon mass; this factor is the same order of magnitude as the reduction due to $\tan^2\theta$. It is