Study of K^+ Forward Scattering from the Reaction $\pi^- p \to K^+ \Sigma(1385)^-$ at 4.5 and 6 GeV/c*

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Experimental data are presented for the forward scattering of K^+ from the reaction $\pi^- p \to K^+ \Sigma(1385)^-$. This "forbidden" peripheral scattering can not be explained by any simple kinematic effects in the $\Lambda K^+ \pi^-$ final state. s-channel resonances, two-particle exchange, or a single "exotic"-meson exchange in the t channel are examined as possible explanations of this effect.

Since there has been no strong experimental evidence for an $I=\frac{3}{2}$ $K\pi$ resonance from production experiments, the observation of the "forbidden" peripheral scattering[1] of K^+ from $\pi^- p \to K^+ \Sigma(1385)^-$ has renewed the interest and speculation concerning its possible existence.[2] However, this "forbidden" scattering has been given other interpretations such as kinematic reflections in the $\Lambda K^+ \pi^-$ final state, s-channel resonances, and two-particle (for example, $K^\pm, \pi^\pm$ or $\rho^\pm, K^{*\pm}$) exchange in the t channel.[3] In this Letter we report the observation of this "forbidden" forward reaction: $\pi^- p \to K^+ \Sigma(1385)^-$ at 4.5 GeV/c. We cannot explain these results by a simple kinematic reflection in our data. The shape of the differential cross section at this energy, when compared with those at lower energies, suggests that an s-channel resonance is not a likely interpretation for this effect. We also present the upper limit of the cross section for this "forbidden" forward scattering at 6 GeV/c. These data lead to an energy dependence of the cross section for this peak of $s^{-3.7\pm0.4}/\ln s$ for incident π^- momenta from ~2 to 6 GeV/c ($s \simeq 5$ to 10 GeV^2).

The data for this analysis came from (a) a 500 000-picture exposure to π^- mesons at 4.5 GeV/c in the Stanford Linear Accelerator Center (SLAC) 82-in. hydrogen bubble chamber, and (b) a 230 000-picture exposure to π^- mesons at 6 GeV/c in the Brookhaven National Laboratory (BNL) 80-in. hydrogen bubble chamber. Events were measured on the BNL flying-spot digitizer (FSD). The reactions of interest are as follows[4]:

		4.5 GeV/c	6 GeV/c
(1)	$\pi^- p \to \Lambda K^+ \pi^-$	1226 events	373 events
(2)	$\to \Sigma^0 K^+ \pi^-$	560 events	172 events
(3)	$\to \Lambda^0 K^0 \pi^0$	420 events	99 events

The Dalitz plots and mass-squared projections for Reactions (1) and (2) at 4.5 GeV/c are shown in Fig. 1. The $K_{1/2}^*(890)^0$ and $K_{1/2}^*(1420)^0$ bands are the dominant feature of these reactions. Therefore to search for $\Sigma(1385)^-$ production, events in the K^* bands (0.84 to 0.96 GeV and 1.34 to 1.48 GeV as shown in the Dalitz plots) must be removed from the subsequent analysis. A marked enhancement in the $\Lambda\pi^-$ mass spectrum is evident after removal of K^*'s [solid region in Fig. 1(a)].[5] This enhancement does not depend on the exact choice of the limits of these K^* bands and thus it is not associated with the K^*'s. We identify this enhancement with the $\Sigma(1385)^-$ since the fitted mass of 1392 ± 8 MeV and width of 32^{+16}_{-10} MeV are in good agreement with the established values for this resonance. There is no similar structure in the $\Sigma^0\pi^-$ mass spectrum [Fig. 1(c)], a point which will be discussed later.

To investigate how the $\Sigma(1385)^-$ is produced in Reaction (1) at 4.5 GeV/c, the $\Lambda\pi^-$ mass-squared distributions are shown in Fig. 1(b) for different selections of $\hat{\pi}^- \cdot \hat{K}^+$. The forward ($\hat{\pi}^- \cdot \hat{K}^+ \sim +1$) and backward ($\hat{\pi}^- \cdot \hat{K}^+ \sim -1$) scatterings dominate the angular distribution. The cross section in the "forbidden" forward hemisphere ($0 \le \hat{\pi}^- \cdot \hat{K}^+ \le 1$) corresponds to 0.9 ± 0.25 μb and can be described by e^{bt} with $b = 2\pm1$ GeV^{-2} for $|t| < 0.5$ GeV^2. The upper limit for the similar cross section at 6 GeV/c is 0.3 μb at the 99% confidence level. Because the forward scattering of the K^+ in the reaction $\pi^- p \to K^+ \Sigma(1385)^-$ cannot be explained by the exchange of any single known particle in the t channel, we must, therefore, consider other possible explanations of this peripheral K^+ production as follows:

(1) *Kinematic effect.*—Unlike broad resonances such as $\Delta(1238)$, the $\Lambda\pi^-$ peak is narrow (~35 MeV) and well defined (1392 ± 8 MeV), and in general is difficult to generate by a kinematic reflection of $K\pi$ scattering without invoking other final state interactions. For example, the calculations of Berger[6] predict a width for the $\Lambda\pi^-$ peak due to kinematic reflection of the order of 200 MeV. In this respect, we have examined the

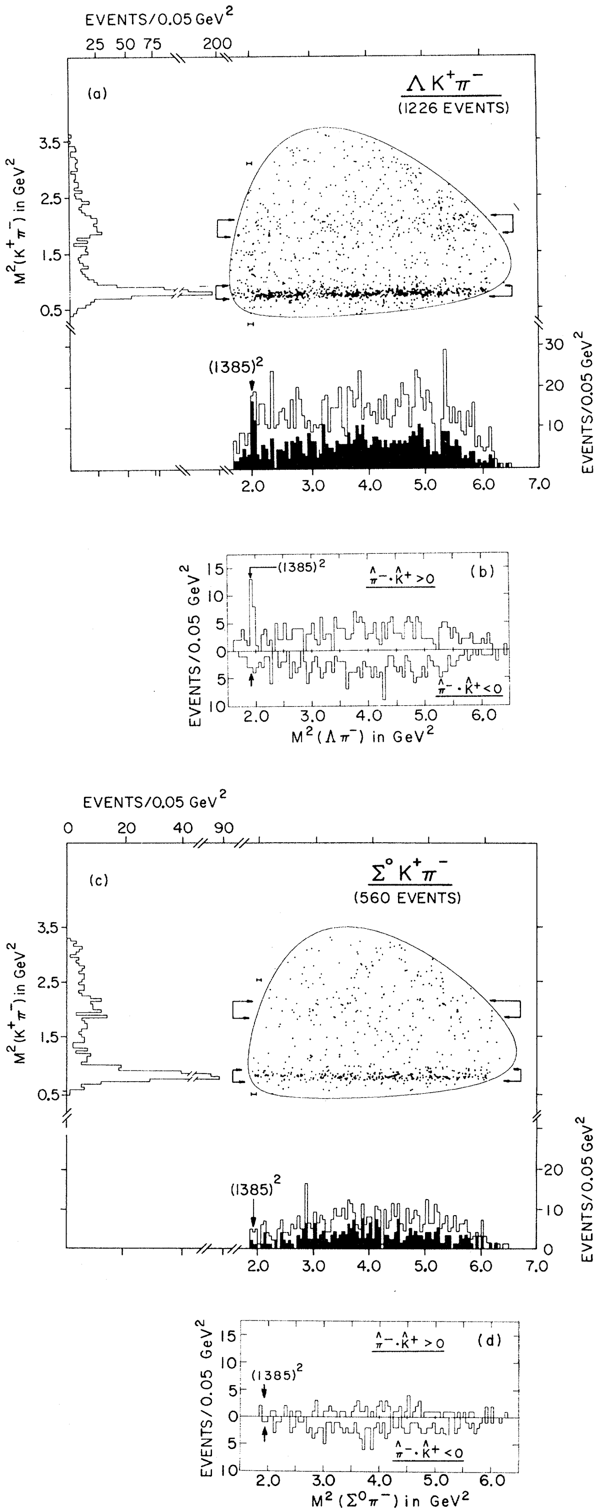

FIG. 1. (a), (c) Dalitz plots and their mass projections for final state (1) and (2) at 4.5 GeV/c. Solid histograms are for events outside the $K_{1/2}$*(890) and $K_{1/2}$*(1420) bands. (b), (d) Mass-squared projections for $\Lambda\pi^-$ and $\Sigma^0\pi^-$, respectively, for different selections of $\hat{\pi}^-\cdot\hat{K}^+$ as shown.

$K^+\pi^-$ angular distributions as a function of $K^+\pi^-$ mass for both $\Lambda K^+\pi^-$ and $\Sigma^0K^+\pi^-$ final states. These distributions (not shown), found in terms of either forward-backward asymmetry or $K^+\pi^-$ moments, for events inside and outside the K^* regions, are very similar for the $\Lambda K^+\pi^-$ and $\Sigma^0K^+\pi^-$ final states. Therefore, a relevant test can be made in the reaction $\pi^-p\rightarrow\Sigma^0K^+\pi^-$: If there were kinematic reflections producing the $\Lambda\pi^-$ peak in the reaction $\pi^-p\rightarrow\Lambda K^+\pi^-$ the same mechanism would produce a $\Sigma^0\pi^-$ peak in the reaction $\pi^-p\rightarrow\Sigma^0K^+\pi^-$. With no final-state interaction, the magnitude should be proportional to the number of events in the $\Sigma^0K^+\pi^-$ final state and the mass perhaps displaced from the $\Sigma^-(1385)$. However the absence of a $\Sigma^0\pi^-$ peak (where eight events are expected above background and none is seen) in the $\Sigma^0K^+\pi^-$ final state, as shown in Fig. 1(c), suggests that the $\Lambda\pi^-$ peak is not due to the kinematic effect, and is indeed the $\Sigma(1385)^-$. From the established branching ratio $\Sigma(1385)^-\rightarrow(\Sigma^0\pi^-)/(\Lambda\pi^-)$, we expect that less than two $\Sigma^0\pi^-$ events can be due to $\Sigma(1385)^-$. This is certainly consistent with our observation.

We have also examined the distribution of the angle between the target proton and the Λ in the $\Sigma(1385)^-$ rest frame (not shown) and found it to be symmetric. This distribution is again not consistent with a kinematic reflection.

We conclude that a simple kinematic reflection due to $K^+\pi^-$ scattering is not consistent with our observation without invoking an additional final-state interaction between π^- and Λ, as suggested by Berger.[6] This additional assumption, of course, is somewhat indistinguishable from two-particle exchange in the t channel, a possibility which we discuss later.

(2) *s-channel resonance(s).*—A single s-channel isobar could produce both the forward and backward peaking in the reaction $\pi^-p\rightarrow K^+\Sigma(1385)^-$ and $K^0\Sigma(1385)$. In the reaction $\pi^-p\rightarrow K^0\Sigma(1385)^0$ at 4.5 GeV/c, the K^0 production angular distribution,[7] Fig. 2(h), shows a strong forward ($\hat{\pi}^-\cdot\hat{K}^0\sim+1$) signal but with no backward peak ($\hat{\pi}^-\cdot\hat{K}^0\sim-1$). This is not in a good agreement with the $K^+\Sigma(1385)^-$ angular distribution[7,8] [Fig. 2(d)]. Therefore a single s-channel resonance interpretation is not a likely one. However, many isobars are reported in this mass region and the different behavior of angular distributions between $K^+\Sigma(1385)^-$ and $K^0\Sigma(1385)^0$ may be explained by complicated interference effects among the isobars. We see no s dependence in the angular distributions of $\pi^-p\rightarrow K^+\Sigma(1385)^-$ and $K^0\Sigma(1385)^0$ in

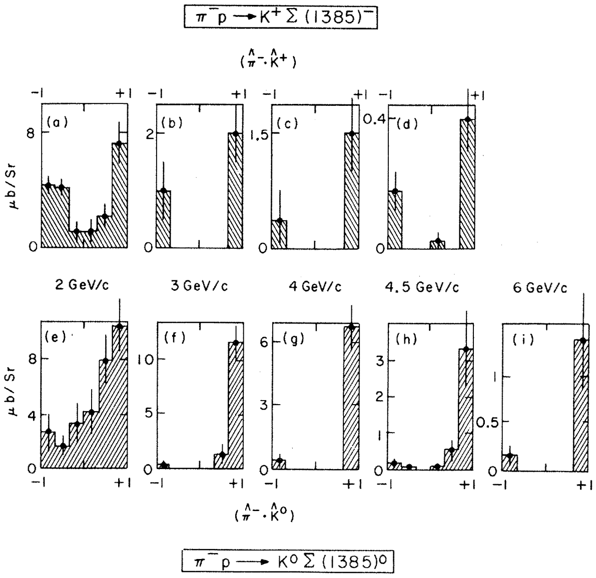

FIG. 2. (a)-(d) $d\sigma(\pi^- p \to K^+\Sigma(1385)^-)/d\Omega$ for incident pion momenta of 2-4.5 GeV/c. (e)-(i) $d\sigma(\pi^- + p \to K^0 + \Sigma(1385)^0)/d\Omega$ for indicent pion momenta of 2-6 GeV/c. Data for 2-4 GeV/c come from Ref. (1).

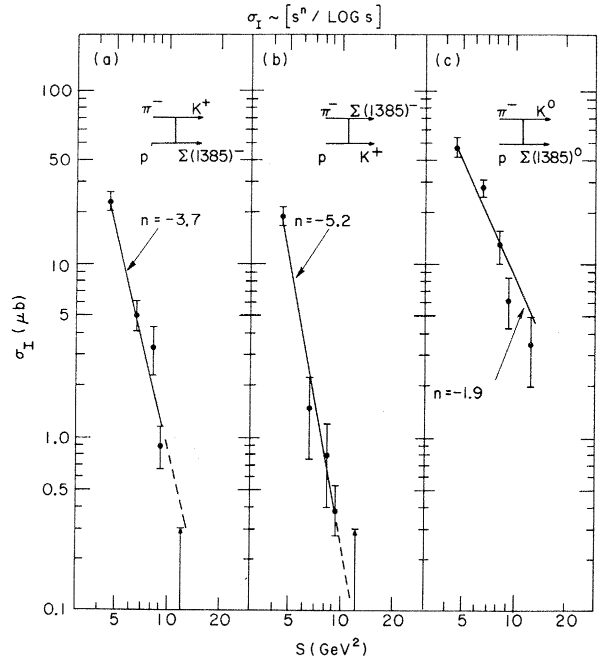

FIG. 3. Integrated cross sections σ_I vs s. Solid lines are the fit to the data as shown. See text for details.

Fig. 2 above 2 GeV/c, indicating the t-channel and u-channel exchanges to be the simplest description from the duality[9] point of view. To support this conjecture, the energy behavior of cross sections in the "forbidden" forward hemisphere and the "allowed" backward hemisphere from $\pi^- p \to K^+\Sigma(1385)^-$, and in the "allowed forward hemisphere from $\pi^- p \to K^0\Sigma(1385)^0$, for incident pion momenta ~2 to 6 GeV/c, are shown in Figs. 3(a), 3(b), and 3(c), respectively. The data are fitted well with the form $s^n/\ln s$,[10] where $n_1 = -3.7 \pm 0.4$ for the forward "forbidden," $n_2 = -5.2 \pm 0.5$ for the backward "allowed," and $n_3 = -1.9 \pm 0.3$ for the forward "allowed" reactions.[11] The last two values are in agreement with the "hyperon"-exchange and "meson"-exchange behavior deduced from other processes.[12] We therefore suggest that the forward K^+ production, above 2 GeV/c π^- incident momentum, can be best described by a t-channel and not an s-channel effect.

It is interesting to note that the s dependence for the differential cross section at the forward direction for $\pi^- p \to K^+\Sigma^-$ is steep ($\sim s^{-11}$) and has been attributed to an s-channel $\Delta(1950)$ effect.[13] In this connection, the s dependence of the forward cross section for $\pi^- p \to K^+\Sigma(1385)^-$ is, however, less steep ($\sim s^{-4}$).

(3) *Two-particle or single exotic exchange in t channel.* – Experimentally these two possibilities are difficult to distinguish from each other. From the simple Regge-pole model, the cross section for the forward hemisphere can be expressed as $s^{2\alpha_0 - 2}/\ln s$, where α_0 is the value of a Regge trajectory at $t = 0$ in the Chew-Frautschi plot.[10] From Fig. 3(a) we obtain the experimental value $\alpha_0 = -0.9 \pm 0.2$. If this "forbidden" forward peak is indeed due to a single $I = \frac{3}{2}$ "exotic" meson exchange, then this may imply an exotic meson having a mass of ~1.0 (1.4) GeV for $J^P = 0^+$ (1^-) assuming the slope of the trajectory to be 1.

For two-particle or "cut" contribution in the t channel,[3] α_0 takes a form of $(\alpha_0^1 + \alpha_0^2) - 1$, where α_0^1 and α_0^2 are the values of two possible trajectories at $t = 0$. For the examples $(\pi^\pm, K^\pm)$ and $(\rho^\pm, K^{*\pm})$, $\alpha_0(\pi^\pm, K^\pm) \simeq -1.25$ and $\alpha_0(\rho^\pm, K^{*\pm}) \simeq -0.4$. The large error in the experimental α_0 precludes any positive identification of which one if either of these examples of two-particle exchanges may be responsible for the K^+ forward scattering.[14] However, for $(\pi^\pm, K^\pm)$ exchange, one would expect the slope (b) of the differential cross section to be steep in disagreement with what we observe ($b = 2 \pm 1$), whereas for $(\rho^\pm, K^{*\pm})$ exchange, the slope would be about 4 which is not incompatible with our result.[3] More data, particularly at higher energies, should be able to answer these questions.

To summarize, we have observed the "forbidden" forward scattering of K^+ from the reaction

$\pi^- p \to K^+\Sigma(1385)^-$. This forward peak cannot be explained by kinematic reflections of the $K^+\pi^-$ scattering in the $\Lambda K^+\pi^-$ final state. The $K^+\Sigma(1385)^-$ angular distribution at 4.5 GeV/c as well as those from lower energies suggest that this peak is not due to s-channel effects. We therefore have to face the possibility of either two-particle or a single "exotic" exchange in the t channel to describe the production of the "forbidden" peripheral peak. In any case, more data are needed for this reaction, $\pi^- p \to K^+\Sigma(1385)^-$ and, in particular, the line-reversed reaction $K^- p \to \pi^+\Sigma(1385)^-$ in order to compare their energy dependences and angular distributions.[15]

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[1]M. A. Abolins *et al.*, Phys. Rev. Lett. 22, 427 (1969); P. M. Dauber *et al.*, Phys. Lett. 29B, 609 (1969); P. L. Hoch, private communication.

[2]For example, J. L. Rosner, in *Experimental Meson Spectroscopy*, edited by C. Baltay (Columbia U. Press, New York, 1970), p. 499.

[3]D. Amati, S. Fubini, and A. Stanghellini, Phys. Lett. 1, 29 (1962); C. B. Chiu and J. Finkelstein, Nuovo Cimento 59A, 92 (1969); C. Michael, Phys. Lett. 29B, 230 (1969); N. W. Dean, Nucl. Phys. B7, 311 (1968).

[4]Ionization information from the FSD was used to veto hypotheses. Then an event was assigned to Reaction (1) if it successfully fitted that hypothesis; to Reaction (2) if it successfully fitted that hypothesis but did not fit Reaction (1) and if the missing neutral mass squared was ≤ 1.7 (GeV)^2; to Reaction (3) if it fitted only that reaction and if the missing mass squared and its error were ≤ 0.1 (GeV)^2. For Reaction (2) the decay angular distribution of $\Sigma^0 \to \Lambda\gamma$ (not shown) was isotropic indicating no serious selection biases.

[5]No enhancement is present in the $\Sigma^-(1385)$ region if only events in the K^* bands are plotted.

[6]E. Berger, Phys. Rev. Lett. 23, 1139 (1969).

[7]The angular distributions are shown after a background subtraction and correction for the K^* bands which were removed.

[8]For an s-channel Δ isobar the branching ratio would be $(\Delta \to \Sigma^0 K^0)/(\Delta \to \Sigma^- K^+) = 2$, whereas if the s-channel resonance were a $N_{1/2}^*$ the branching ratio would be $(N_{1/2}^* \to \Sigma^0 K^0)/(N_{1/2}^* \to \Sigma^- K^+) = \frac{1}{2}$. Therefore an s-channel Δ as well as $N_{1/2}^*$ can be ruled out by two standard deviations by comparing the backward signals in Fig. 2.

[9]For a review of the subject, see J. D. Jackson, Rev. Mod. Phys. 42, 12 (1970).

[10]Limited statistics in the forward "forbidden" peaks preclude exact determinations of $d\sigma/dt$ at $t_{\rm min}$. Therefore, we assume the forward peak can be expressed as $d\sigma/dt \sim s^{2(\alpha-1)}$ where $\alpha = \alpha_0 + \alpha' t$. The integrated cross section

$$\sigma_I = \int_{-\infty}^{t_{\rm min}} \frac{d\sigma}{dt} dt$$

can be expressed as $\simeq s^n/\ln s$, where $n = 2(\alpha_0 - 1)$ assuming $\alpha' > 0$.

[11]When the data are fitted with the form $\sim s^n$, we find $n_1 = -4.2 \pm 0.4$, $n_2 = -5.8 \pm 0.5$, and $n_3 = -2.5 \pm 0.3$.

[12]D. R. O. Morrison, Phys. Lett. 22, 528 (1966).

[13]See, for example, C. W. Akerlof, University of Michigan Report No. UM-HE-70-19, 1970 (unpublished).

[14]Further, if two single particles were exchanged the amplitudes could have an interference which could lead to a polarization of the Λ from the $\Sigma^-(1385)$ decay. However, there are too few events in our data to obtain reliable polarization information.

[15]An experimental comment is in order here. Since the reaction $K^- p \to \Lambda\pi^-\pi^+$ is dominated by $\Sigma(1385)^+$ as well as ρ^0, f^0, etc., a missing-mass search for $\Sigma(1385)^-$ by detecting π^+ *only* from the reaction $K^- p \to \pi^+ +$ anything is probably fruitless; also the production cross section of $\Sigma(1385)^-$ is small and the possible signal will be buried under overwhelming reflections from other strongly produced resonances as stated above. This, certainly, is the case for the reaction $\pi^- p \to K^+\Lambda\pi^-$ investigated in this experiment.