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[11] One way out of the analyticity violation would be to say that the cross section will keep breaking.

LOW-MASS $K\overline{K}$ SYSTEMS PRODUCED IN π^-p INTERACTIONS BELOW 5 BeV/c*

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In a study of $K\overline{K}$ pairs produced in π^-p interactions from 1.5 to 4.2 BeV/c, we observe the $K_1^0K_1^0$ threshold enhancement at all beam momenta, and the φ meson at beam momenta below 2.3 BeV/c. There are no significant enhancements in the K^0K^- system near threshold.

Recent studies have suggested the existence of several low-mass $K\overline{K}$ enhancements: (a) a threshold effect in the $K_1^0K_1^0$ system attributed to a large $I=0$ scattering length[1,2]; (b) a $K_1^0K_1^0$ peak near $M=1060$ MeV with full width $\Gamma \simeq 80$ MeV interpreted as evidence for an $I=0$ resonant state[3,4]; and (c) a narrow peak in the $K_1^0K^\pm$ system at $M\simeq 1025$ MeV with $\Gamma \simeq 40$ MeV, interpreted as an $I=1$ resonance.[5,6] In addition, the low-mass $K_1^0K_2^0$ and K^+K^- final states exhibit peaks from decay of the well-established $I^GJ^P=0^-1^-$ φ meson at 1020 MeV. In this Letter we discuss the behavior of the $K\overline{K}$ systems observed in the reaction $\pi^-+p\to K+\overline{K}+N$ below 5 BeV/c. Both the low-mass $K_1^0K_1^0$ threshold enhancement and the φ meson are observed in the $I=0$ final states; no significant deviations from phase space are apparent in the $I=1$ states at low effective mass.

The film was obtained using the Lawrence Radiation Laboratory's 72-inch hydrogen bubble chamber in the course of a systematic study of π^-p interactions within the interval 1.5 to 4.2 BeV/c. The experimental details have been discussed by Hess.[7] The observed numbers of events and corresponding cross sections are given in Table I.

(A) $K_1^0K_1^0$ threshold enhancement.—The $M(K_1^0K_1^0)$ distribution is shown in Fig. 1(a) for events with $\Delta^2(n)\le 0.5$ (BeV/c)^2. The $\Delta^2(n)$ distribution in Fig. 1(b) demonstrates that this selection includes most events with $M(K_1^0K_1^0)\le 1.075$ BeV. The strong concentration at low $\Delta^2(n)$ in this mass interval suggests production through pion exchange. In this case, the isospin is zero for the initial $\pi\pi$ system since C is +1 for the $K_1^0K_1^0$ system. A quantitative test of the isospin may be made with the charge-independence triangle inequality. For $I=1$ in the observed $K_1^0K_1^0$ system, we have

$$\{2\sigma(\pi^-+p\to(K\overline{K})^0+n)\}^{1/2} \le \{\sigma(\pi^++p\to(K\overline{K})^++p)\}^{1/2} + \{\sigma(\pi^-+p\to(K\overline{K})^-+p)\}^{1/2}. \quad (1)$$

If we use the data of Lander et al.[8] for $\pi^++p\to(K\overline{K})^++p$ at 3.5 BeV/c and our data at 3.2 BeV/c, (1) becomes

$$(60\pm 20)^{1/2}\le(6.0\pm 6.0)^{1/2}+(1.4\pm 1.4)^{1/2}, \quad (2)$$

where the values are given in microbarns. Since the inequality is poorly satisfied, we conclude that $I=0$ for the low-mass $K_1^0K_1^0$ system. The distributions in decay angle and Treiman-Yang angle are shown in Figs. 1(c) and 1(d) for all events with $M(K_1^0K_1^0)\le 1.075$ BeV; they are consistent with the isotropic distributions expected for a $J^P=0^+$ state.

In experiments above 5 BeV/c,[3,4] the same reaction yields a peak in the $K_1^0K_1^0$ mass distribution near 1060 MeV, with $\Gamma\approx 80$ MeV, suggesting a resonant state. The dashed curve in Fig. 1(a), representing phase space multi-

Table I. Cross sections for the observed final states.

Final state	Momentum interval (BeV/c)	Number of events[a]	Cross section (μb)
$p+K^0+K^-$	1.6 to 2.4	249	31.9 ± 3.5
	2.9 to 3.3	228	65.1 ± 5.3
	3.8 to 4.2	95	65.7 ± 7.9
$n+K_1^0+K_1^0$	1.6 to 2.4	157	15.8 ± 4.2
	2.9 to 3.3	201	45.3 ± 4.1
	3.8 to 4.2	68	36.6 ± 5.1
$n+K^++K^-$	1.5 to 2.3	86	39 ± 10
	2.9 to 3.3	90	195 ± 60
	3.8 to 4.2	48	370 ± 130

[a] The numbers of events in the final states pK^0K^- and $nK_1^0K_1^0$ include only those events where the $K_1^0\to\pi^++\pi^-$ decays are seen in the chamber. The number of events in the nK^+K^- final state include only those events where a K^+ or K^- decay is seen in the chamber. The cross sections were corrected for those efficiencies.

plied by a Breit-Wigner resonance, is in poor agreement with the present data; the enhancement is more naturally interpreted as the manifestation of a large scattering length in the $I=0$ $K\bar{K}$ system. For quantitative comparison we have used the Chew-Low formula[9] modified by the Selleri form factor.[10] If we use the zero-effective-range approximation[11] and detailed balancing, the $I=0$ S-wave $K\bar{K}$ production cross section becomes

$$\sigma_0(\pi+\pi\to K+\bar{K})=(4\pi k_K/k_\pi^{\,2})2b_0[(1+b_0k_K)^2+(a_0k_K)^2]^{-1}, \tag{3}$$

where $A_0=a_0+ib_0$ is the S-wave $K\bar{K}$ scattering length, and k_π (k_K) is the momentum of either pion (or K meson) in the $\pi\pi$ c.m. system. Then

$$\sigma(\pi^-+\pi^+\to K_1^0+K_1^0)=(\tfrac{1}{3})(\tfrac{1}{4})\sigma_0(\pi+\pi\to K+\bar{K}). \tag{4}$$

The data are reasonably well fitted[12] with a_0 between 2 and 6 F, if $b_0\simeq0.6a_0-0.5$ F. The calculated Δ^2 distribution using these parameters is shown in Fig. 1(b).

(B) φ meson.—Since the φ meson decays predominantly into $K_1^0+K_2^0$ and K^++K^-, we must study its production in the reaction $\pi^-+p\to K^++K^-+n$. For an event to be fitted to this final state, at least one of the charged kaons must decay in the chamber. Each event fitting the K^+K^-n hypothesis was examined on the scan table for consistency of track ionization with calculated values. The reliability of this procedure decreased at higher momenta, since the tracks were more frequently near minimum ionization. We estimate that the contamination in low-momentum events finally accepted is less than 10%; the contamination could be as high as 50% near 4.2 BeV/c.

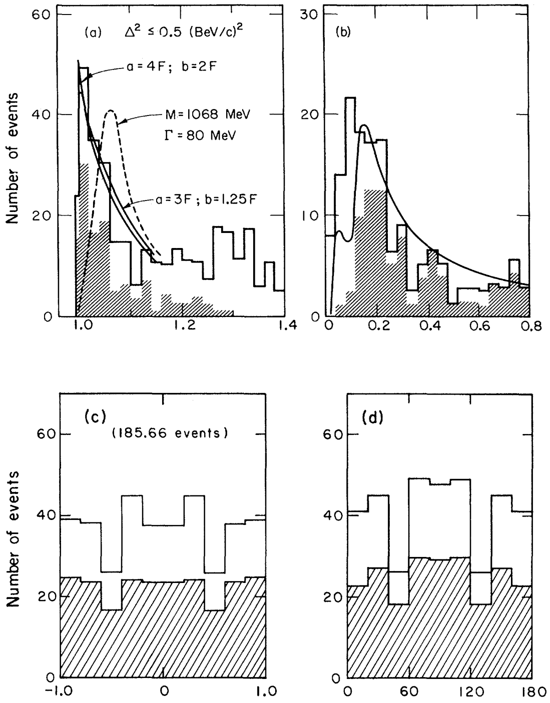

FIG. 1. Data from $nK_1^0K_1^0$ final states at all beam momenta. The events shown have been weighted for the detection efficiency of the decay $K_1\to\pi^++\pi^-$. The average weight is 1.3. Shaded events have a beam momentum less than 2.3 BeV/c. (a) $K_1^0K_1^0$ effective mass distribution. Curves compare the zero-effective-range approximation with a resonance shape having $M=1068$ MeV and $\Gamma=80$ MeV. (b) Distribution of $\Delta^2(n)$ for events with $M(K_1^0K_1^0)\le1075$ MeV. The curve is the prediction of one-pion exchange with the Selleri form factor. The structure in the curve results from combining data obtained at several beam momenta. (c), (d) Histograms of (c) the decay cosine ($=\hat{P}_K\cdot\hat{P}_{\text{beam}}$ in the $K\bar{K}$ system) and (d) the Treiman-Yang angle for events with $M(K_1^0K_1^0)\le1075$ MeV. Two points have been plotted for each event.

The distribution in $M(K^+K^-)$ is shown in Fig. 2(a) for events with beam momentum between 1.5 and 2.3 BeV/c. The striking feature of the data is the sharp peak at $M(K^+K^-)=1021\pm4$ MeV with $\Gamma=10\pm3$ MeV. When the experimental resolution of 5 MeV is unfolded, the values are consistent with those accepted for the φ meson, i.e., $M_\varphi=1019.5$ MeV and Γ_φ

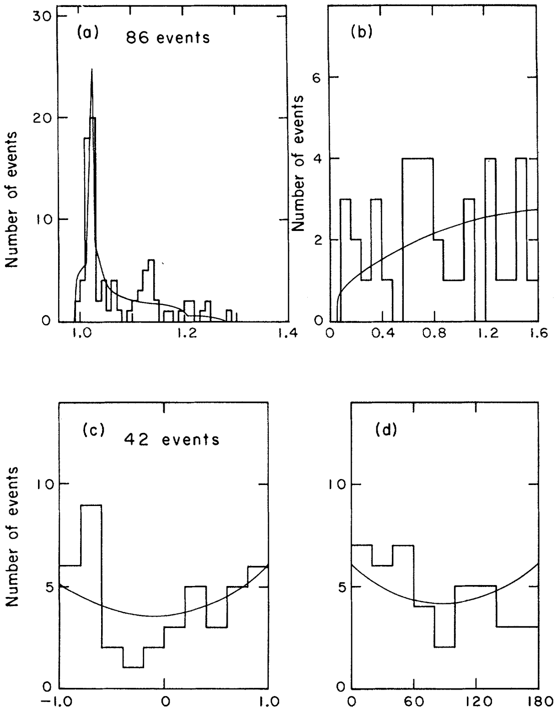

FIG. 2. Data from nK^+K^- final states at beam momenta below 2.3 BeV/c. (a) K^+K^- effective-mass distribution. The curve is for 40% φ production, 40% phase space, and 20% threshold enhancement. (b), (c), (d) Histograms of (b) $\Delta^2(n)$, (c) decay cosine, and (d) Treiman-Yang angle for events with $1005 \leq M_{K^+K^-} \leq 1035$ MeV. Curves are Monte Carlo distributions for isotropic production and decay angular distributions.

Table II. Cross sections for production of the threshold enhancement and the φ meson.

Process	Momentum (BeV/c)	Cross section (μb)
$\pi^- + p \to n + (\text{T.E.})$,[a]	1.8 to 2.2	7.9 ± 2.0
$(\text{T.E.}) \to K_1^0 K_1^0$	2.9 to 3.3	7.5 ± 2.5
	3.8 to 4.2	9.0 ± 3.7
$\pi^- + p \to n + \varphi$	1.58 to 1.71	29.0 ± 15.0
	1.8 to 2.2	30.0 ± 8.0
	2.58 to 2.63	0.0 ± 9.0
	2.9 to 3.3	6.0 ± 8.0
	3.8 to 4.2	15.0 ± 20.0

[a] T. E. stands for threshold enhancement. The reported cross sections have been corrected for the unobserved K_1^0 decays only.

$=3.3$ MeV. The $\Delta^2(n)$ distribution in Fig. 2(b) for events with $M(K^+K^-)$ between 1005 and 1035 MeV differs markedly from the corresponding distribution for $K_1^0K_1^0$ events, shown shaded in Fig. 1(b). This provides further evidence that the K^+K^- peak has an origin different from the S-wave threshold enhancement.

To determine detection efficiencies, events corresponding to $\pi^- + p \to \varphi + n$ were generated with the Monte Carlo program FAKE.[13] Because of limited data, calculations are shown in Figs. 2(b), 2(c), and 2(d) only for isotropic production and decay distributions. Although the decay angular distribution is consistent with being isotropic, a better fit is obtained when linear and quadratic terms are included. The linear term may result from interference with background arising from the S-wave threshold enhancement. The curve in Fig. 2(a) represents 20% threshold enhancement estimated from the effect observed in the K_1K_1 final state and calculated detection efficiencies, 40% φ production, and 40% phase space. Production cross sections are given in Table II; they were calculated using the branching fraction $(\varphi \to K^+ + K^-)/(\varphi \to \text{all decays}) = 0.48 + 0.04$.[14]

In the simplest model of φ production through ρ exchange, the decay angular distribution is proportional to $\sin^2\theta$. We do not observe this correlation, but absorptive effects can modify the distribution significantly.[15] However, the observed production and decay distributions are similar to those reported by Kraemer et al.[16] for $\pi^+ + n \to \omega + p$. Cross sections for $\pi^+ + n \to \omega + p$ and $\pi^- + p \to \varphi + n$ may be related through SU(3) and charge symmetry (or any model involving ρ exchange). Available data[16-19] are compared in Fig. 3. The abscissa is the c.m. momentum for the final state; the energy de-

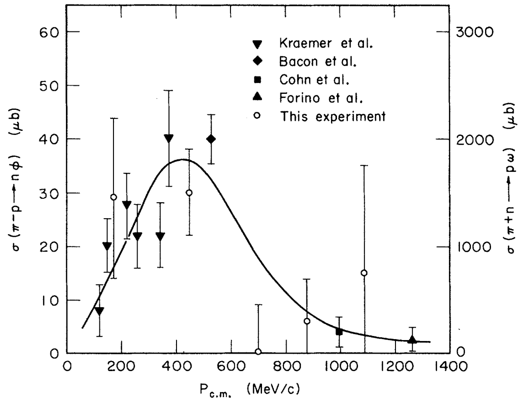

FIG. 3. Total cross sections for $\pi^+ + n \to p + \omega$ from other experiments (solid symbols) and $\pi^- + p \to n + \varphi$ from this experiment (open symbol). The abscissa is the c.m. momentum of the final-state particles. The ordinates differ by a factor of 50.

pendences correspond roughly when the ordinate for $\pi^- + p \rightarrow \varphi + n$ is increased by ~50. Other experiments[20-22] suggest that the ratio of cross sections for $\pi^+ + p \rightarrow \omega + N^{*++}$ and $\pi^+ + p \rightarrow \varphi + N^{*++}$ is ~70.

(C) The $I = 1$ $K\bar{K}$ system.—We searched in the reaction $\pi^- + p \rightarrow K^- + K^0 + p$ for the $K^0K^\pm$ state observed in $p\bar{p}$ annihilations.[5,6] Our data show no evidence for the production of such a state; the one-standard-deviation upper limit to its cross section is 1 μb (3 μb) at 2 BeV/c (3.2 BeV/c). This observation is consistent with the assumption that (a) most low-mass $K\bar{K}$ systems are produced by π or ρ exchange, and (b) the low-mass $K^0K^\pm$ state has quantum numbers $I^GJ^P = 1^-0^+$. Should the charged $K\bar{K}$ enhancement reflect the existence of a bound state below threshold, decay into $\pi + \eta$ is expected to dominate; this may correspond to the sharp peak observed by Kienzle *et al.*[23] and by Oostens *et al.*[24] at around 965 MeV.

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$$\frac{d\sigma}{dM} = \frac{f^2}{2\pi}\frac{2M^2k_K}{M_\pi^2k_\pi P_\pi^2}\left[\int F(\Delta^2)\frac{\Delta^2 d\Delta^2}{(\Delta^2 + M_\pi^2)^2}\right]\sigma(\pi + \pi \rightarrow K + \bar{K}),$$

where $f^2 = 0.16$. Although this form factor was not deduced for the reaction we consider, it should account qualitatively for deviations from the one-pion-exchange model. Our conclusions are not sensitive to the detailed form factor used.

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