Partial-Wave Analysis of the $K^+\bar{K}^0\pi^-$ System

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We have performed a partial-wave analysis of the $K^+K_S^0\pi^-$ system produced in the reaction $\pi^-p \to K^+\bar{K}^0\pi^-n$ at 8 GeV/c. We present the results of the analysis of 30740 events in the mass range 1.24–1.60 GeV/c^2, with $0.0 \leq -t < 1.0$ GeV^2/c^2. In the 1.28-GeV/c^2 mass region, we see evidence for a $J^{PG}=0^{-+}$ resonance in addition to the resonant 1^{++} wave. We observe a 0^{-+} resonance and possibly a small 1^{++} resonance in the 1.42-GeV/c^2 region. We also observe a 1^{++} state near 1.5 GeV/c^2.

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The 1.4–1.5-GeV/c^2 region of nonstrange mesons is a subject of great controversy. Various experiments studying the $K\bar{K}\pi$ and $\eta\pi\pi$ final states in hadronic reactions, hadronic J/ψ decay, and two-photon interactions have reported a state near 1.42 GeV/c^2 with J^{PC} determined alternatively as 0^{-+} (Refs. 1 and 2) or 1^{++}.[3] On the other hand, $K\bar{K}\pi$ spectrum observed in radiative J/ψ decay is dominated by a broad spectrum near 1.45 GeV/c^2 with $J^{PC}=0^{-+}$,[4] sometimes interpreted as a glueball with a small admixture of quarks.[5] Our present experiment reveals the complicated structure of the $K\bar{K}\pi$ system in the mass range from 1.24 to 1.6 GeV/c^2.

We present results of a partial-wave analysis of the $K^+K_S^0\pi^-$ system produced in the reaction $\pi^-p \to K^+\bar{K}^0\pi^-n$ at 8 GeV/c. A total of 30740 events in the mass range 1.24 to 1.60 GeV/c^2 with $0.0 \leq -t < 1.0$ GeV^2/c^2 was collected at the BNL Multiparticle Spectrometer. In a previous publication,[6] we presented results of a Dalitz-plot analysis of about 30% of the present data. Reference 6 also contains descriptions of the apparatus and trigger requirements.

The observed $K^+K_S^0\pi^-$ mass spectrum and the spectrum calculated from the partial-wave-analysis (PWA) fit are shown in Fig. 1. Also shown are the corresponding spectra for $0.45 \leq -t < 1.0$ GeV^2/c^2. The distribution is dominated by two peaks at 1.28 and 1.42 GeV/c^2. A smaller peak is also seen near 1.51 GeV/c^2. A fit of three Breit-Wigner functions and a polynomial background gives the following mass, width, and number of events for each peak:

Mass (MeV/c^2)	Width (MeV/c^2)	Number of events
1285 ± 1	22 ± 2	4750 ± 100
1419 ± 1	66 ± 2	8800 ± 200
1512 ± 4	35 ± 15	600 ± 200

For the seven points in the region 1.48–1.55 GeV/c^2, including the third Breit-Wigner function improved the value of the χ^2 from 25.5 to 1.5 in this mass region.

The $K^+\bar{K}^0\pi^-$ system was described as a superposition of states characterized by spin, parity, and G parity, J^{PG}, absolute value of the projection of spin on the quantization axis, M, and reflectivity (naturality of the exchanged particle), η. We applied the parametrization of the spin-density matrix of Chung and Trueman[7] which ensures that the conditions of positivity, parity conservation, and rank 2 are automatically satisfied with the minimum number of parameters.

We assumed that the final three-meson system is produced in a two-step process involving two isobars: $K^*(890)$ and $a_0(980)$ [was $\delta(980)$]. For a given $K^+\bar{K}^0\pi^-$ mass, the state is fully specified by five variables: the isobar mass and the polar and azimuthal angles for the primary and secondary decays.

The decay amplitude $a_0(980) \to K\bar{K}$ is poorly known. We used the two-channel formula:

$$T \propto [m_R^2 - m^2 - im_R(a_1q_1 + a_2q_2)m_t/m]^{-1},$$

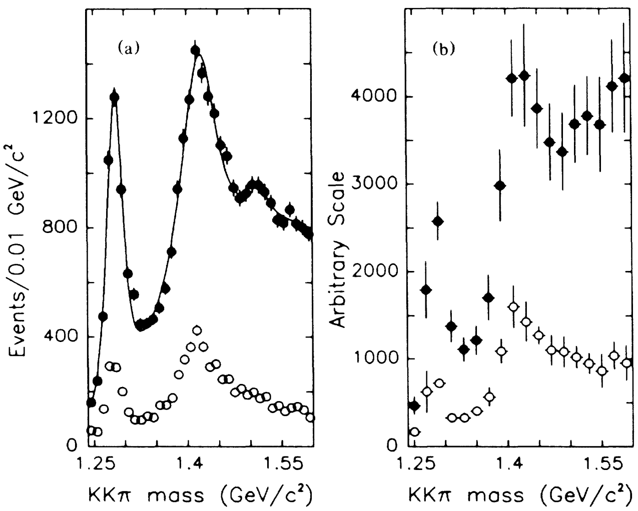

FIG. 1. $K^+K^0_S\pi^-$ mass. The filled circles are for $0.0\le -t < 1.0$ GeV$^2/c^2$ and the open circles are for $0.45\le -t<1.0$ GeV$^2/c^2$. (a) Observed spectrum. The fit is described in the text. (b) Spectrum calculated from the PWA fit (corrected for finite acceptance).

where m is the $K^+\bar{K}^0\pi^-$ mass, $m_t=m_K+m_{\bar{K}}$, and q_1 and q_2 denote breakup momenta in the $\eta\pi$ and $K\bar{K}$ channels. The parameters m_R, $r=a_2/a_1$, and a_1 can be varied so as to reproduce the observed mass and width of the $a_0(980)$ in the $\eta\pi$ channel. a_1 and a_2 are dimensionless constants related to the decay coupling constants. The parameters used in the present analysis were $m_R=978$ MeV/c^2, $r=0.5$, and $a_1=0.212$.[8] We also allowed for an incoherent phase-spacelike, isotropic background.

We used a PWA program written for this experiment.[9] This program uses the extended maximum-likelihood method and includes the effect of finite acceptance in the normalization integrals.

The following waves were needed to fit the data: $J^{PG}=0^{-+}$, 1^{++}, 1^{+-}, and 1^{--} with all possible values of M; 2^{+-} for $M\le 1$; and $J^{PG}M^{\eta}=1^{-+}0^-$ and $2^{++}0^-$. For $J^{PG}=0^{-+}$ and 1^{++} both decay channels, $a_0\pi$ and K^*K, were allowed. However, we found that the waves $1^{++}(a_0)$ and $1^{++}(K^*)$ were too much alike to distinguish between them below the K^*K threshold and only one of them could be included at a time. We also found that in the region $1.40<M(K^+\bar{K}^0\pi^-)<1.60$ GeV/c^2, where both $1^{++}(a_0)$ and $1^{++}(K^*)$ could be included in the fit, $1^{++}(a_0)$ was small. The best choice was to allow $1^{++}(a_0)$ for $M(K^+\bar{K}^0\pi^-)<1.34$ GeV/c^2 and $1^{++}(K^*)$ for $M(K^+\bar{K}^0\pi^-)>1.34$ GeV/c^2. The waves $0^{-+}(a_0)$ and $0^{-+}(K^*)$ were varied simultaneously with an arbitrary degree of coherence between them.

The analysis was carried out independently for three t regions: $0.0\le -t<0.2$ GeV$^2/c^2$, $0.2\le -t<0.45$ GeV$^2/c^2$, and $0.45\le -t<1.0$ GeV$^2/c^2$. The results, in the form of the effective number of events attributed to the most important spin-parity states, summed over t, are given in Fig. 2, and, for particular decay modes, in Fig. 3. The phases of $0^{-+}(a_0)$ and $0^{-+}(K^*)$ with respect to $1^{++}0^+(K^*)$, for the three t regions discussed, are shown in Fig. 4. We checked the quality of the fits

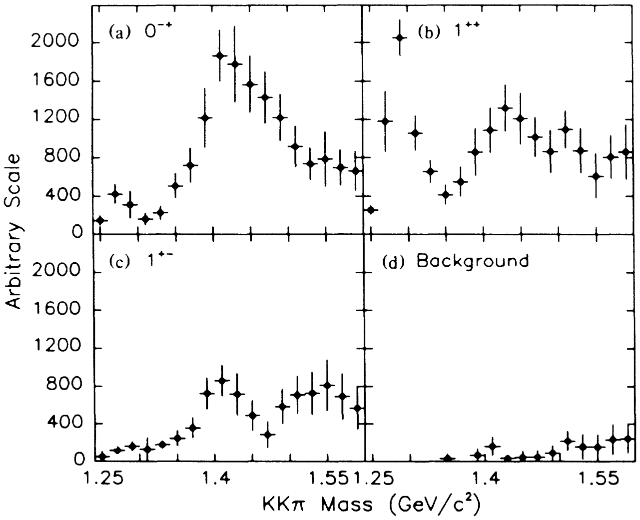

FIG. 2. Major spin-parity components of the $K^+\bar{K}^0\pi^-$ system for $0.0\le -t<1.0$ GeV$^2/c^2$. Scale as in Fig. 1(b). (a) $0^{-+}(a_0)$ and (K^*), (b) $1^{++}(a_0)$ and (K^*), (c) $1^{+-}(K^*)$, and (d) background.

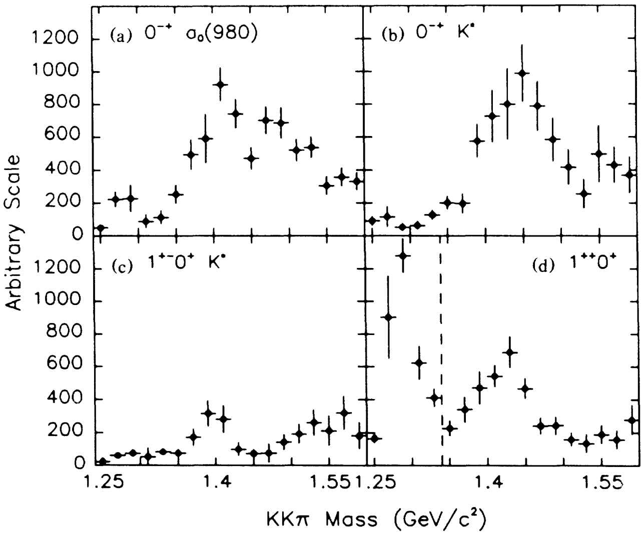

FIG. 3. Spin-parity components of the $K^+\bar{K}^0\pi^-$ system for $0.0\le -t<1.0$ GeV$^2/c^2$. Scale as in Fig. 1(b). (a) $0^{-+}(a_0)$, (b) $0^{-+}(K^*)$, (c) $1^{+-}0^+(K^*)$, (d) $1^{++}0^+(a_0)$ for $M(K^+\bar{K}^0\pi^-)<1.34$ GeV/c^2 and $1^{++}0^+(K^*)$ for $M(K^+\bar{K}^0\pi^-)>1.34$ GeV/c^2 (the dashed line indicates the division).

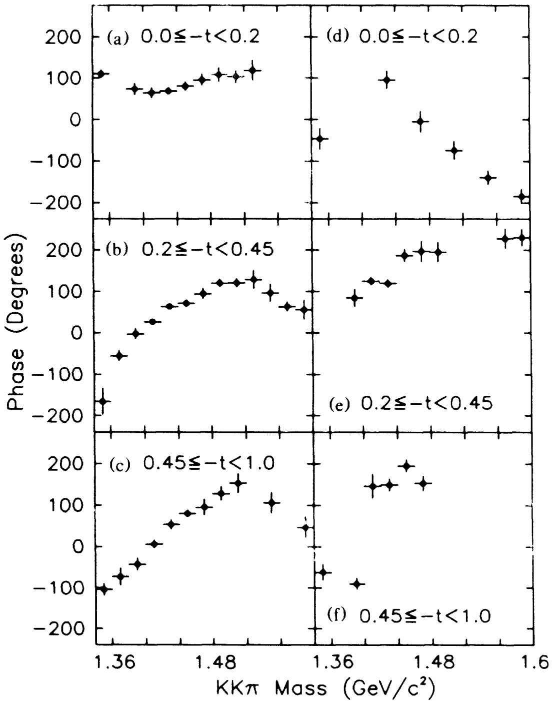

FIG. 4. Phases with respect to $1^{++}0^{+}(K^*)$, for the three t regions discussed in the text. If the density matrix element is within two standard deviations of zero, the corresponding phase is not shown. (a)-(c) $0^{-+}(a_0)$ and (d)-(f) $0^{-+}(K^*)$.

by comparing experimental distributions of $K\pi$ and $K\bar{K}$ masses and decay angles with distributions for Monte Carlo events, run through a trigger-simulation program and weighted with the probability function obtained in the PWA fits. We found the data and Monte Carlo events to be in excellent agreement. The salient features of the fit are as follows.

(1) The peak at 1.28 GeV/c^2 is dominated by $f_1(1285)$ [was $D(1285)$], which decays to $K^+\bar{K}^0\pi^-$ through the intermediate state $a_0\pi$. There is also an indication of a resonance in the 0^{-+} wave in the $f_1(1285)$ region, previously seen in $\eta\pi\pi$,[2,10] where it exhibits a small peak and the phase difference (not shown) between this wave and the resonant $1^{++}(a_0)$ is constant, implying that both are resonating.

(2) The structure at 1.42 GeV/c^2 is complicated. The waves contributing to the observed peak are 0^{-+}, 1^{++}, and 1^{+-}. This finding is in general agreement with our previous results (Ref. 6). The strongest contribution, about 50%, comes from 0^{-+}. The underlying resonance structure can be understood only by the study of the interference effects between these waves.

(3) The 0^{-+} waves become more important as $|t|$ increases (not shown).

(4) The natural-parity waves 1^{-+}, 1^{--}, 2^{++}, and 2^{+-} (not shown) are small below 1.50 GeV/c^2. The 2^{++} wave is substantial above 1.50 GeV/c^2 with $0.0 \leq -t < 0.2$ GeV^2/c^2.

For all three t regions considered, the waves $0^{-+}(a_0)$ and $1^{++}0^{+}(K^*)$ are highly coherent and their relative phase is well measured (Fig. 4). For $0.2 \leq -t < 0.45$ GeV^2/c^2 and $0.45 \leq -t < 1.0$ GeV^2/c^2, the phase of $0^{-+}(a_0)$ is rising through about 300° in the mass range 1.35 to 1.50 GeV/c^2, and then begins to fall. This phase variation is evidence of a resonant $0^{-+}(a_0)$ wave and predominantly nonresonant $1^{++}0^{+}(K^*)$ wave at $-t$ above 0.2 GeV^2/c^2. Because of the likely presence of several overlapping resonances, any estimate of their parameters would be necessarily model dependent. Both the phase motion and the intensity distribution of the wave $0^{-+}(a_0)$ are consistent with the presence of one resonance near 1.40 GeV/c^2 or two resonances between 1.40 and 1.50 GeV/c^2. Contrary to the two larger $-t$ regions, for the low $-t$ region ($0.0 \leq -t < 0.2$ GeV^2/c^2), the phase of $0^{-+}(a_0)$ relative to $1^{++}0^{+}(K^*)$ is almost constant. Therefore, the possibility of a resonance in 1^{++} at $-t$ below 0.2 GeV^2/c^2 cannot be ruled out. This 1^{++} resonance would contribute approximately 10% of the total peak in the 1.42-GeV/c^2 region. The phase of $0^{-+}(K^*)$ for $0.2 \leq -t < 0.45$ GeV^2/c^2 and $0.45 \leq -t < 1.0$ GeV^2/c^2 seems to be similar to the phase of $0^{-+}(a_0)$, although not as well measured. The peaking in the $1^{+-}0^{+}(K^*)$ intensity near 1.40 GeV/c^2 could be associated with the h_1', the missing $I=0$ member of the $b_1(1235)$ [was $B(1235)$] nonet.[11] However, no strong conclusion can be drawn from the observed phase motion (not shown).

The fitted parameters of the peak at 1.51 GeV/c^2 are consistent with the mass and width of the $f_1(1530)$ [was $D'(1530)$], a likely member of the a_1 nonet.[11,12] Also, the phase of $0^{-+}(a_0)$ measured relative to $1^{++}0^{+}(K^*)$, which increases in the 1.42-GeV/c^2 region, reverses direction and begins falling above 1.50 GeV/c^2, consistent with the presence of a 1^{++} resonance. For the low $-t$ region, the 2^{++} wave also seems to be important in this mass region. A more complete study of this mass region will be given in a future publication.

In summary, from a partial-wave analysis of the reaction $\pi^- p \to K^+\bar{K}^0\pi^- n$ at 8 GeV/c, we have observed a 0^{-+} resonance in addition to the well known 1^{++} resonance in the 1.28-GeV/c^2 mass region. We have established the resonance behavior of the 0^{-+} wave in the 1.42-GeV/c^2 region and found some evidence for 1^{++} and 1^{+-} resonances in this mass region (the latter would be identified with the h_1'). We also have evidence for a resonant 1^{++} wave state at 1.51 GeV/c^2.

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