Partial-Wave Analysis of $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$

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Results from a partial-wave analysis of the decay $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$ in the $K_S^0 K^{\pm}\pi^{\mp}$ invariant-mass range 1.35–1.6 GeV/c^2 are presented. Within the isobar model, the data in this mass range are best described by a mixture of 0^{-+} and 1^{++} amplitudes, corresponding to the $K^*\bar{K}$+c.c. (P wave), $K^*\bar{K}$+c.c. (S wave), and $a_0(980)\pi$ (S wave) channels. These results show that $\eta(1430)$ is not a $J^{PC}=0^{-+}$ $a_0(980)\pi$ resonance, but a mixture of overlapping states.

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During the past decade, the study of isoscalar $K\bar{K}\pi$ states has received considerable attention, since one or more of these states[1-3] may lie outside the nonets predicted by the quark model. One such state, $\eta(1430)$ [formerly $\iota(1440)$], has been considered a gluonium candidate[1] since its first observation in the decay $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$ by the Mark II experiments.[4]

The basic properties of $\eta(1430)$ are poorly understood: Results from an early analysis,[5] which determined that $\eta(1430)$ decays primarily through the $J^{PC}=0^{-+}$ $a_0(980)\pi$ (S wave) channel, have not been substantiated in more recent analyses.[6] The latter observed a significant 0^{-+} K^*K decay channel,[7] and an $\eta(1430)$ invariant-mass distribution which is poorly characterized as a single S-wave Breit-Wigner resonance. With the intention of addressing these issues, we report herein the results of an isobar-model[8] partial-wave analysis (PWA) of the decay $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$.

The present analysis is based on a sample of 5.8×10^6 produced J/ψ events collected with the Mark III detector[9] at the SLAC e^+e^- storage ring SPEAR. Though $\eta(1430)$ has been detected in the $K_S^0 K^{\pm}\pi^{\mp}$, $K^+K^-\pi^0$, and $K_S^0 K_S^0 \pi^0$ channels,[4-6,10] we analyze only the $K_S^0 K^{\pm}\pi^{\mp}$ channel; of the three decay modes, it has the highest statistics, the least background, and the highest acceptance, and is therefore the most suitable for the PWA.

Candidate events for the decay $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$, $K_S^0 \rightarrow \pi^+\pi^-$ are required to have four charged tracks and one to six neutral showers. A pair of oppositely charged tracks is identified as a K_S^0 if the two track projections in the plane perpendicular to the beam axis intersect, and if the $\pi^+\pi^-$ invariant mass is in the range 0.478–0.513 GeV/c^2. Five-constraint kinematic fits of events with an identified K_S^0 are performed to the hypothesis $J/\psi \rightarrow \gamma K_S^0 K^{\pm}\pi^{\mp}$ for each shower in the event. Particles assigned to be kaons (pions) by the kinematic fit must not be identified as pions (kaons) by time-of-flight (TOF) measurement.[11] The best fit with a χ^2 probability of greater than 5% is retained for further analysis.

The $K_S^0 K^{\pm}\pi^{\mp}$ invariant-mass distribution [Fig. 1(a)] shows a strong and markedly asymmetric $\eta(1430)$ signal. A Dalitz plot for the 1.35–1.45-GeV/c^2 $K_S^0 K^{\pm}\pi^{\mp}$ mass region [Fig. 1(b)] shows a cluster of events in the region of low $K_S^0 K^{\pm}$ mass, while a Dalitz plot for the 1.45–1.55-GeV/c^2 mass region [Fig. 1(c)] shows clear evidence for K^* bands. The higher-mass Dalitz plot displays a population density characteristic of a 0^{-+} state decaying to K^*K: a dense cluster of events due to constructive interference where the K^* bands cross, and a vanishing population in the middle of each band, the signature of a longitudinally polarized (i.e., helicity=0) K^*.

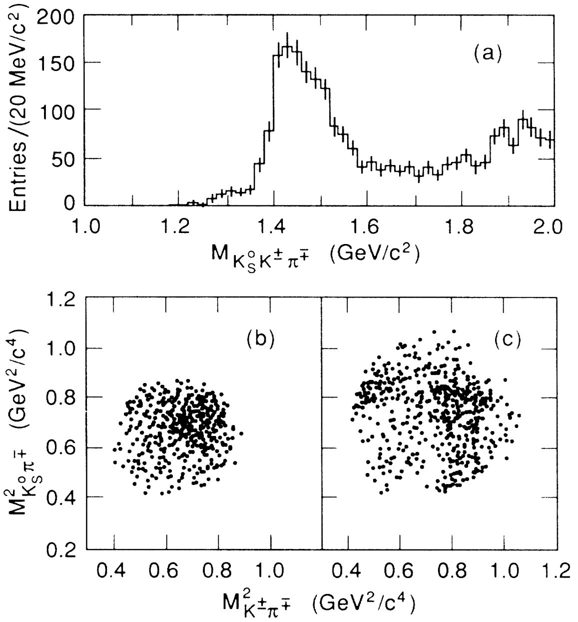

FIG. 1. (a) Invariant $K^0_S K^\pm \pi^\mp$ mass distribution; (b) Dalitz plot for $1.35 < M_{K^0_S K^\pm \pi^\mp} < 1.45$ GeV/c^2; (c) Dalitz plot for $1.45 < M_{K^0_S K^\pm \pi^\mp} < 1.55$ GeV/c^2.

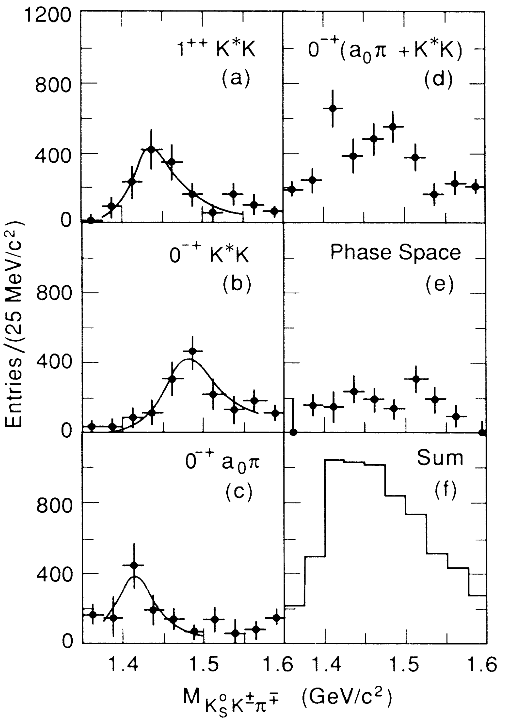

FIG. 2. Acceptance-corrected partial-wave intensities for $1.35 < M_{K^0_S K^\pm \pi^\mp} < 1.60$ GeV/c^2. Plotted are the (a) 1^{++} K^*K S-wave, (b) 0^{-+} K^*K, (c) 0^{-+} $a_0(980)\pi$, (d) summed 0^{-+}, and (e) incoherent phase-space intensities. In (f) is a histogram of the data, also corrected for acceptance. Accompanying plots (a), (b), and (c) are curves corresponding to the χ^2 fits described in the text.

The quasi-two-body structure and associated spin-parity of the $K^0_S K^\pm \pi^\mp$ system are more closely investigated in a PWA.[12] A model is formulated using a set of interfering amplitudes, the relative magnitudes and phases of which are estimated in a maximum-likelihood fit. Using the measured four-vectors of the final state, we employ an invariant-tensor formalism[12,13] which is used to construct the amplitudes for the process $J/\psi \to \gamma X$, where the system X is in a well-defined J^{PC} state, and decays through a specified two-body channel. All 0^{-+}, 1^{++}, and 1^{-+} amplitudes accessible to the $a_0(980)\pi$ and K^*K (Ref. 14) channels are considered. The K^* mass dependence is parametrized using a relativistic P-wave propagator[15] with nominal values for K^* mass and width;[16] the $a_0(980)$ state is described by a coupled-channel model.[17] To account for events not described by the above amplitudes, we include an additional amplitude which is not allowed to interfere with the others, and corresponds to a three-body phase-space decay of X.

Fits are performed in 25-MeV/c^2 $K^0_S K^\pm \pi^\mp$ mass intervals spanning the range 1.35–1.60 GeV/c^2. Various combinations of amplitudes are fitted separately; log likelihoods are then compared to determine the dominant amplitudes. The 1^{-+} K^*K and 1^{++} K^*K D-wave amplitudes are found to contribute insignificantly to the likelihood, and are thus excluded. Because of limited charged-track acceptance and statistics our technique cannot distinguish unambiguously between a 0^{-+} $a_0(980)\pi$ amplitude and a 1^{++} $a_0(980)\pi$ amplitude with polarization such that a uniform $\cos\theta_{a_0}$ distribution[18] is produced (we hereafter refer to this circumstance as "flat polarization"). Near the K^*K threshold, the 1^{++} K^*K S-wave and 1^{++} $a_0(980)\pi$ amplitudes also become indistinguishable, the result of limited statistics and phase space. Consequently, we cannot rule out the presence of a flat-polarized 1^{++} $a_0(980)\pi$ component in the data which is attributed to the 0^{-+} $a_0(980)\pi$ channel, or the presence of a 1^{++} $a_0(980)\pi$ component near the K^*K threshold, and we fit only to the 1^{++} K^*K (S wave), 0^{-+} K^*K (P wave), and 0^{-+} $a_0(980)\pi$ (S wave) amplitudes.[19] The resulting intensities, normalized to the number of produced $J/\psi \to \gamma K^0_S K^\pm \pi^\mp$ events, appear in Fig. 2.

The stability of the fit results is tested under two differing conditions, which include (i) repeating the PWA described above with a series of variations in data selection criteria, $a_0(980)$ parametrization,[20] initial parameter values, and mass binning, and (ii) repeating the analysis including various mixtures of the additional amplitudes: 0^{-+} $[a_2(1320)\pi]$, 1^{++} $[a_2(1320)\pi]$, 2^{++} $[K^*K]$, and 2^{-+} $[a_0(980)\pi, a_2(1320)\pi, K^*K]$. In each test, the dominant features of the fit remain unchanged; the 0^{-+} $a_0(980)\pi$, 0^{-+} K^*K, and 1^{++} K^*K S-wave amplitudes retain the highest significance, and consistently account for ~75% of the total signal analyzed. Moreover, the resulting intensity distributions do not vary with respect to each other by more than 20%. In test (ii), no significant increases in the likelihood are observed, and the fraction of incoherent phase space is reduced by an amount which increases as more waves are added.

Two-body invariant-mass projections predicted from the fit results are compared to the data in Fig. 3. The comparisons indicate that reasonable fits have been achieved; similarly good agreement is observed in the angular production variables. As an additional check of fit quality, we perform a series of Monte Carlo experiments with the assumption that the fitted parameters are correct, and compare the experimental log likelihood with those obtained from the simulations. The mass regions 1.400-1.425, 1.425-1.450, and 1.475-1.500 GeV/c^2 are checked in this manner, and are found to be well simulated by the fitted model.

The intensity spectra in Figs. 2(a)-2(c) are suggestive of three states in the 1.35-1.60-GeV/c^2 region. Given the limited statistics and lack of a slowly varying reference amplitude, the measured phases cannot be used to verify this possibility. We nevertheless extract resonance parameters and branching ratios by performing χ^2 fits, using relativistic Breit-Wigner amplitudes, to the K^*K S-wave, K^*K P-wave, and $a_0(980)\pi$ S-wave intensities in the mass intervals 1.375-1.575, 1.375-1.550, and 1.375-1.500 GeV/c^2, respectively. Masses, widths, and branching fractions appear in Table I [the corresponding curves are plotted over the intensities in Figs. 2(a)-2(c)] with statistical and systematic errors. The systematic errors reflect variations in these results caused by (i) fitting each intensity spectra in larger or smaller mass intervals, (ii) fitting PWA results for data obtained using different selection criteria, and (iii) fitting the summed 0^{-+} intensities [Fig. 2(d)], using either coherent or incoherent sums of two Breit-Wigner amplitudes. The systematic errors on the branching ratios include an 8.5% uncertainty in the number of produced J/ψ events.

In a comparison with other experimental results in the 0^{-+} channel, we note that the $a_0(980)\pi$ resonance parameters in Table I are consistent with those of the $\eta(1400)$ state, which was first observed[21] in a PWA of the process $\pi^- p \to \eta\pi^+\pi^- n$ at 8.06 GeV/c, and more recently observed by the Mark III Collaboration in a preliminary PWA of $J/\psi \to \gamma\eta\pi^+\pi^-$.[22] Studies of the process $\pi^- p \to K_S^0 K^+ \pi^- n$ at 8 GeV/c[23] and $\pi^- p \to K_S^0 K_S^0 \pi^0 n$ at 21 GeV/c[24] also report 0^{-+} $a_0(980)\pi$ structure[25] near 1420 MeV/c^2, along with higher-mass contributions from 1^{++} and 0^{-+} K^*K. The above comparisons suggest that the same signals are seen both in radiative J/ψ decays and in $\pi^- p$ interactions in the ~1.4-1.5-GeV/c^2 region; this argues against the idea that $\eta(1430)$ is a gluonium state. The identification of two pseudoscalar states [i.e., a ≈1420-MeV/c^2 $a_0(980)\pi$ state and a ≈ 1490-MeV/c^2 K^*K state] in the $\eta(1430)$ region, however, would increase the number of present isoscalar candidates for the first radially excited 0^{-+} nonet to three,[26] indicating that a non-$q\bar{q}$ state may still exist between 1.2 and 1.6 GeV/c^2.

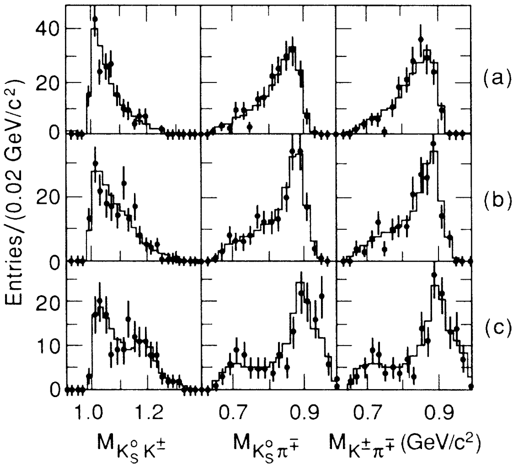

FIG. 3. Distributions in two-body invariant masses $M_{K_S^0 K^\pm}$, $M_{K_S^0 \pi^\mp}$, and $M_{K^\pm \pi^\mp}$ for the data (points) and Monte Carlo experiments (histograms) in the $K_S^0 K^\pm \pi^\mp$ mass intervals (a) 1.400-1.425 GeV/c^2, (b) 1.425-1.450 GeV/c^2, and (c) 1.475-1.500 GeV/c^2.

In the 1^{++} channel, the K^*K peak we observe is reasonably described by the $f_1(1420)$ parameters estimated from the reaction $J/\psi \to \omega K\bar{K}\pi$,[27] but has a mass which is significantly higher than the $f_1(1420)$ mass measured in two-photon[28] and central-production[29] experiments. If our entire K^*K peak is attributed to the $f_1(1420)$ meson, its branching ratio in radiative J/ψ decays (assuming a 100% K^*K decay) is larger than that estimated for $f_1(1285)$ production,[30]

$$B(J/\psi \to \gamma f_1(1285)) \sim (4.1\text{-}8.4) \times 10^{-4},$$

suggesting that $f_1(1420)$ and $f_1(1285)$ are not ideally mixed. From the ratio of the above branching ratios, we

TABLE I. Results of χ^2 fits to the intensity distributions.

Amplitude	M_X (MeV/c^2)	Γ_X (MeV/c^2)	$10^3 B(J/\psi \to \gamma X, X \to K\bar{K}\pi)$
1^{++} K^*K	$1443^{+7}_{-6}{}^{+3}_{-2}$	$68^{+29}_{-18}{}^{+8}_{-9}$	$0.87^{+0.14}_{-0.14}{}^{+0.14}_{-0.11}$
0^{-+} $a_0(980)\pi$	$1416^{+8}_{-8}{}^{+7}_{-5}$	$54^{+37}_{-21}{}^{+13}_{-24}$	$0.66^{+0.17}_{-0.16}{}^{+0.24}_{-0.15}$
0^{-+} K^*K	$1490^{+14}_{-8}{}^{+3}_{-16}$	$91^{+67}_{-31}{}^{+15}_{-38}$	$1.03^{+0.21}_{-0.18}{}^{+0.26}_{-0.19}$

estimate a mixing angle for the 1^{++} nonet in the range $\theta_A \sim 46°\text{-}56°$, which agrees well with a weighted average of measurements[31] from two-photon experiments.

It has been proposed[3] that $f_1(1420)$ is a K^*K molecule, and that $f_1(1530)$ (Ref. 32) is possibly the isoscalar partner of $f_1(1285)$. Although we observe no clear evidence for $J/\psi \to \gamma f_1(1530)$ in the present analysis, we cannot rule out such a process in the K^*K channel for branching ratios on the order of 10^{-4}.

In summary, this analysis has shown that the $K\bar{K}\pi$ signal observed in radiative J/ψ decay in the 1.35-1.60-GeV/c^2 region decays predominantly through K^*K, in both the 0^{-+} and 1^{++} channels. Below ≈ 1.42 GeV/c^2, the $K\bar{K}\pi$ spectrum is more difficult to describe. Our fit results in this region indicate a small, but significant, contribution from 0^{-+} $a_0(980)\pi$, but cannot rule out a similar contribution from 1^{++} $a_0(980)\pi$.

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[1] J. F. Donoghue, K. Johnson, and B. A. Li, Phys. Lett. **99B**, 416 (1981); K. Ishikawa, Phys. Rev. Lett. **46**, 978 (1981); M. Chanowitz, Phys. Rev. Lett. **46**, 981 (1981).

[2] M. Chanowitz, Phys. Lett. B **187**, 409 (1987).

[3] J. L. Rosner, in *Proceedings of the Second International Conference on Hadron Spectroscopy, Tsukuba, Japan, 1987,* edited by Y. Oyangi, K. Takamatsu, and T. Tsuru (National Laboratory for High Energy Physics, Tsukuba, 1987), p. 395.

[4] D. Scharre *et al.*, Phys. Lett. **97B**, 329 (1980).

[5] C. Edwards *et al.*, Phys. Rev. Lett. **49**, 259 (1982).

[6] W. J. Wisniewski, in *Proceedings of the Second International Conference on Hadron Spectroscopy* (Ref. 3), p. 88; T. H. Burnett, in *Glueballs, Hybrids and Exotic Hadrons,* edited by S. U. Chung, AIP Conference Proceedings No. 185 (American Institute of Physics, New York, 1989), p. 102.

[7] All references to K^*K imply $K^*\bar{K}+\bar{K}^*K$.

[8] D. Herndon, P. Söding, and R. J. Cashmore, Phys. Rev. D **11**, 3165 (1975).

[9] D. Bernstein *et al.*, Nucl. Instrum. Methods Phys. Res. **226**, 301 (1984).

[10] J. Richman, Ph.D. thesis, California Institute of Technology, Report No. CALT-68-1231, 1985.

[11] An identified kaon (pion) is a track with a TOF measurement which is closer to that expected for a kaon (pion) than for a pion (kaon).

[12] J. Drinkard, Ph.D. thesis, University of California, Santa Cruz, Report No. SCIPP-90/04, 1990.

[13] C. Zemach, Phys. Rev. **140**, B97 (1965).

[14] The K^*K amplitudes are constructed as G-parity eigenstates, with $G=C=+1$.

[15] J. D. Jackson, Nuovo Cimento **34**, 1644 (1964).

[16] Particle Data Group, M. Aguilar-Benitz *et al.*, Phys. Lett. B **204**, 1 (1988).

[17] S. M. Flatté, Phys. Lett. **63B**, 224 (1976).

[18] The angle θ_{a_0} is defined in the $K\bar{K}\pi$ rest frame as the polar angle of the $K\bar{K}$ system with respect to the $K\bar{K}\pi$ production axis.

[19] The log likelihood ($\mathcal{L}$) from this fit, summed over the five mass intervals between 1.350 and 1.475 GeV/c^2, is 333; when a 1^{++} $a_0(980)\pi$ amplitude is substituted for the 0^{-+} $a_0(980)\pi$ amplitude, we obtain $\mathcal{L}=329$; when both the 0^{-+} and 1^{++} $a_0(980)\pi$ amplitudes are included in the fit, we obtain $\mathcal{L}=361$, and observe destructive interference between the 1^{++} $a_0(980)\pi$ and 1^{++} K^*K amplitudes which gives rise to large fluctuations in these intensities in the lower-mass bins.

[20] N. A. Tornqvist, Ann. Phys. (N.Y.) **123**, 1 (1979); M. Roos and N. A. Tornqvist, Z. Phys. C **5**, 205 (1980); N. A. Tornqvist, Acta Phys. Pol. B **16**, 503 (1985).

[21] A. Ando *et al.*, Phys. Rev. Lett. **57**, 1296 (1986); T. Tsuru, in *Proceedings of the Second International Conference on Hadron Spectroscopy* (Ref. 3), p. 233.

[22] J. Drinkard, in Proceedings of the Fifteenth American Physical Society Division of Particles and Fields General Meeting, Houston, Texas, 1990 (to be published).

[23] A. Birman *et al.*, Phys. Rev. Lett. **61**, 1557 (1989).

[24] M. G. Rath *et al.*, Phys. Rev. D **40**, 693 (1989).

[25] In Ref. 23, the $a_0(980)\pi$ amplitude is shown to be resonant.

[26] Studies of a third candidate, $\eta(1280)$, appear in N. R. Stanton *et al.*, Phys. Rev. Lett. **42**, 346 (1979), and also in Refs. 21.

[27] J. J. Becker *et al.*, Phys. Rev. Lett. **59**, 186 (1987).

[28] H. Aihara *et al.*, Phys. Rev. D **38**, 1 (1988); H. J. Behrend *et al.*, Z. Phys. C **42**, 367 (1989); G. Gidal *et al.*, Phys. Rev. Lett. **59**, 2016 (1987); P. Hill *et al.*, DESY Report No. DESY-88-166, 1988 (unpublished).

[29] T. A. Armstrong *et al.*, Z. Phys. C **34**, 23 (1987); T. A. Armstrong *et al.*, Phys. Lett. B **221**, 216 (1989).

[30] This estimate uses

$$B(J/\psi \to \gamma f_1(1285))B(f_1(1285) \to \eta\pi\pi)$$

and

$$B(J/\psi \to \gamma f_1(1285))B(f_1(1285) \to 4\pi)$$

from Burnett in Ref. 6. These branching ratios are converted into an estimate for $B(J/\psi \to \gamma f_1(1285))$ using the $f_1(1285)$ decay branching ratios listed in Ref. 16.

[31] D. O., Caldwell, in *Glueballs, Hybrids and Exotic Hadrons* (Ref. 6), p. 465.

[32] Ph. Gavillet *et al.*, Z. Phys. C **16**, 119 (1982); D. Aston *et al.*, Phys. Lett. B **201**, 573 (1988).