Study of the $K\bar{K}\pi$ Final State in J/ψ Hadronic Decays

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The reactions $J/\psi\to\omega K\bar{K}\pi$ and $J/\psi\to\phi K\bar{K}\pi$ have been studied in a sample of 5.8×10^6 produced J/ψ decays. The systems $K^\pm K^0_S\pi^\mp$ and $K^+K^-\pi^0$ produced in association with an ω have enhancements in the mass distribution near 1.44 GeV/c^2. The observed angular distributions are consistent with $J^P=1^+$ and do not favor a $J^P=0^-$ assignment. No signal is seen at the nominal $f_1(1285)$ mass. The reverse pattern is observed in the $K\bar{K}\pi$ system produced in association with a ϕ, which shows an enhancement near 1.280 GeV/c^2, and no evidence for structure at 1.4 GeV/c^2.

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The study of the decays $J/\psi\to\{\gamma,\omega,\phi\}X$ is a useful tool in the investigation of the quark and possible gluonium content of a given state X.[1] In this Letter, we describe our use of this technique to examine the $\eta(1440)$,[2] a prime gluonium candidate produced copiously in J/ψ radiative decays, and other more conventional $q\bar{q}$ states such as the $f_1(1285)$ and the $f_1(1420)$.[3]

We report on a study of the $K\bar{K}\pi$ final state in the reactions

$$J/\psi\to\omega K^+K^-\pi^0\to\pi^+\pi^-\pi^0K^+K^-\pi^0, \qquad (1)$$

$$J/\psi\to\omega K^\pm K^0_S\pi^\mp\to\pi^+\pi^-\pi^0K^\pm\pi^+\pi^-\pi^\mp, \qquad (2)$$

$$J/\psi\to\phi K^+K^-\pi^0\to K^+K^-K^+K^-\pi^0, \qquad (3)$$

and

$$J/\psi\to\phi K^\pm K^0_S\pi^\mp \to[K^+K^-,K^0_SK^0_L]K^\pm\pi^+\pi^-\pi^\mp, \qquad (4)$$

based on a sample of 5.8×10^6 produced J/ψ's collected with the Mark III detector at the SLAC e^+e^- storage ring SPEAR.

The Mark III detector has been described in detail elsewhere.[4] Charged particles are identified by time of flight (TOF) and energy loss (dE/dx). A charged particle is called *consistent* with a π, K, or p by TOF (dE/dx) if the measured and calculated times of flight (energy losses) differ by less than three standard deviations for a given mass hypothesis; it is called *identified* with a particle type if it is consistent with only that particle hypothesis.

The first step in the analysis is to select topologically consistent events: those events having the correct number of charged particles and at most four additional neutral showers.[5] At least one track must be consistent (identified) with a $K^\pm$ by TOF (dE/dx). Depending on the reaction, one- to six-constraint kinematic fits are applied, trying all possible photon combinations and/or particle mass assignments. The best combination with regard to particle identification and kinematic fit is retained if the χ^2 probability of the fit, $P(\chi^2_{\rm fit})$, exceeds a minimum value, chosen to optimize the signal-to-background ratio. The particles assigned to be kaons by the kinematic fit are not allowed to be identified as pions by the TOF measurement. To remove background events in which a π^0 is falsely reconstructed from a high-energy photon and a spurious second shower, the requirement $|E_{\gamma1}-E_{\gamma2}|/P_{\pi^0}<0.95$ is imposed in Reactions (1) and (3).

The events $J/\psi\to\omega K^+K^-\pi^0\to\pi^+\pi^-K^+K^-4\gamma$ are selected by six-constraint kinematic fits to the hypothesis $J/\psi\to\pi^+\pi^-\pi^0K^+K^-\pi^0$, requiring at least one track to be consistent with a kaon by TOF and $P(\chi^2_{\rm fit})>0.05$.

The $J/\psi\to\omega K^\pm K^0_S\pi^\mp\to2(\pi^+\pi^-)K^\pm\pi^\mp2\gamma$ are selected by five-constraint kinematic fits to the hypoth-

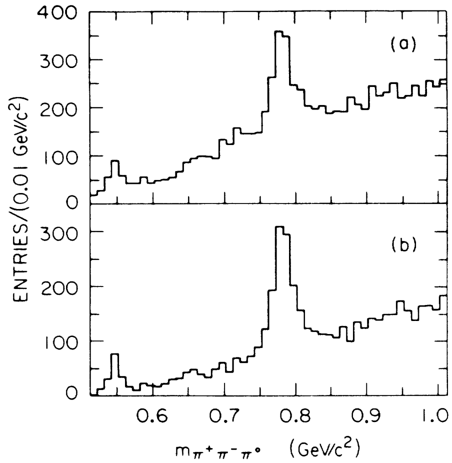

FIG. 1. Three-pion invariant-mass distribution (a) from the reaction $J/\psi \to \pi^+\pi^-\pi^0 K^+K^-\pi^0$, and (b) from $J/\psi \to \pi^+\pi^-\pi^0 K^\pm K_S^0 \pi^\mp$, with (a) two and (b) six possible entries per event.

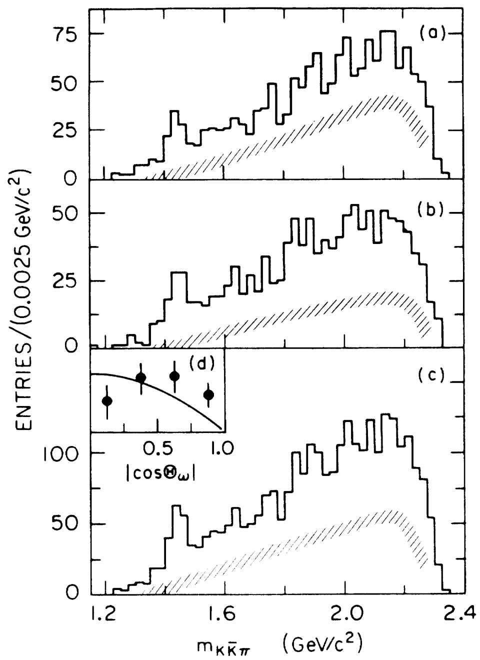

FIG. 2. (a) $K^\pm K_S^0 \pi^\mp$ invariant-mass distribution from $J/\psi \to \omega K^\pm K_S^0 \pi^\mp$; (b) $K^+K^-\pi^0$ invariant-mass distribution from $J/\psi \to \omega K^+K^-\pi^0$; (c) sum. The shaded bands in (a)–(c) show the estimate of the background. (d) Distribution of $|\cos\Theta_\omega|$ with prediction for $J^P = 0^-$ (solid curve).

esis $J/\psi \to \pi^+\pi^-\pi^0 K^\pm \pi^+\pi^-\pi^\mp$, requiring $P(\chi^2_{\rm fit}) > 0.05$. To select events with a K_S^0, at least one of the six possible $\pi^+\pi^-$ combinations must have a vertex detached from the primary vertex and an invariant mass within 0.02 GeV/c^2 of the K_S^0 mass.

Figures 1(a) and 1(b) show the distributions of invariant $\pi^+\pi^-\pi^0$ masses from Reactions (1) and (2). Clear η and ω signals are apparent. Figures 2(a) and 2(b) show the $K^\pm K_S^0 \pi^\mp$ and $K^+K^-\pi^0$ invariant-mass spectra for events in which the mass of the recoiling system is within 0.03 GeV/c^2 of the nominal ω mass; the summed spectrum is displayed in Fig. 2(c). The shaded bands represent the background of events not containing ω's as obtained from 0.06-GeV/c^2-wide sidebands centered 0.09 GeV/c^2 above and below the nominal ω mass. The overall shapes of the mass distributions resemble that of $J/\psi \to \omega K\bar{K}\pi$ or $J/\psi \to \omega K^*(890)K$ phase space.[6] The mass spectra in Fig. 2 show similar signals near 1.4 GeV/c^2, which are correlated with an ω.

For the two data sets and their sum, maximum-likelihood fits are performed in the 1.25–1.80-GeV/c^2 mass region to extract the mass and width of the resonant state. These fits include a quadratic polynominal for the background plus a Breit-Wigner parametrization convoluted with a Gaussian resolution function for the resonance. Since the mass resolution ($\sigma = 0.01$ GeV/c^2) is the same for both channels, it is valid to fit the summed spectrum of Fig. 2(c) to obtain average values. The results of the fits, under the assumption of $K\bar{K}\pi$ phase-space production, are listed in Table I. To account for a possible K^*K decay mode of the resonance a parametrization with a Breit-Wigner shape modified by K^*K phase space is also employed. These fits yield mass values 0.007 GeV/c^2 lower as a result of the rapidly rising phase space above K^*K threshold ($\approx$ 1.38 GeV/c^2). The systematic error is estimated by variation of the fit intervals and background shapes. The error also includes a contribution from unresolved discrepancies in the mass scale (± 0.01 GeV/c^2) and accounts for possible mass shifts due to the $K\bar{K}\pi$ substructure [i.e., K^*K, $a_0(980)\pi$].

The angular distributions of the final-state particles can be used to determine the spin and parity of the intermediate $K\bar{K}\pi$ state. Figure 2(d) shows the acceptance-corrected distribution of the normal of the ω-decay plane in the ω helicity system, Θ_ω, which is obtained by repetition of the mass fits in four bins of $|\cos\Theta_\omega|$, to determine the resonant contribution. The curve predicted for a $J^P = 0^-$ state does not follow the data; a fit yields a probability of 6% for the hypothesis that all signal events arise from a pseudoscalar resonance. This result is supported by a three-channel analysis[7] where the $K\bar{K}\pi$ system is assumed to be composed of a $J^P = 0^-$ state decaying via the $a_0(980)\pi$ intermediate state, a $J^P = 1^+$ state decaying via K^*K, and an isotropic distribution. The analysis assigns the resonant structure to the axial-vector component.

The events $J/\psi \to \phi K^+K^-\pi^0 \to 2(K^+K^-)2\gamma$ are selected by five-constraint kinematic fits to the hypothesis $J/\psi \to 2(K^+K^-)\pi^0$, requiring at least one track to be consistent with a kaon by TOF and

TABLE I. Branching ratios and parameters of resonance X. The first four entries correspond to total branching ratios integrated over the allowed kinematic range.

Mass of X (MeV/c^2)	Width of X (MeV/c^2)	No. of events observed	Reaction $J/\psi \to$	Branching ratio (10^{-4})
·	·	879 ± 41	$\omega K^{\pm} K_S^0 \pi^{\mp}$	$29.5 \pm 1.4 \pm 7.0$
·	·	530 ± 140	$\omega K^* \bar{K} + \mathrm{c.c.}$	$53 \pm 14 \pm 14$
·	·	163 ± 15	$\phi K^{\pm} K_S^0 \pi^{\mp}$	$7.0 \pm 0.6 \pm 1.0$
·	·	155 ± 20	$\phi K^* \bar{K} + \mathrm{c.c}$	$20 \pm 3 \pm 3$
			$\omega X; X \to$	
$1440 \pm 7 ^{+10}_{-17}$	$34 ^{+22}_{-16} \pm 5$	$53 ^{+21}_{-17}$	$K^+ K^- \pi^0$	$1.3 ^{+0.5}_{-0.4} \pm 0.3$
$1442 \pm 7 ^{+10}_{-17}$	$44 ^{+22}_{-16} {}^{+12}_{-5}$	$58 ^{+23}_{-18}$	$K^{\pm} K_S^0 \pi^{\mp}$	$2.1 ^{+0.8}_{-0.7} \pm 0.6$
$1442 \pm 5 ^{+10}_{-17}$	$40 ^{+17}_{-13} \pm 5$	$111 ^{+31}_{-26}$	$K\bar{K}\pi$	$6.8 ^{+1.9}_{-1.6} \pm 1.7$
1285	24	<12	$K\bar{K}\pi$	<1.1 (90% C.L.)
			$\phi X; X \to$	
1420–1440	40–60	<21	$K\bar{K}\pi$	<1.2 (90% C.L.)
1460	92	<32	$K\bar{K}\pi$	<2.1 (90% C.L.)
$1279 \pm 6 \pm 10$	$14 ^{+20}_{-14} \pm 10$	16 ± 6	$K\bar{K}\pi$	$0.6 \pm 0.2 \pm 0.1$

$P(\chi^2_{\mathrm{fit}}) > 0.05$.

The events

$$J/\psi \to \phi K^{\pm} K_S^0 \pi^{\mp} \to K^+ K^- K^{\pm} \pi^+ \pi^- \pi^{\mp}$$

are selected by requiring five and six charged tracks with total charge ± 1 and 0, respectively. In the case of six detected charged tracks [Reaction (4), subset (a)], four-constraint kinematic fits to the hypothesis $J/\psi \to K^+ K^- K^{\pm} \pi^+ \pi^- \pi^{\mp}$ are applied, and the event is retained if $P(\chi^2_{\mathrm{fit}}) > 0.005$. In the case of five detected charged particles [Reaction (4), subset (b)], events are accepted if at least two tracks are consistent with kaons by TOF or dE/dx. One-constraint kinematic fits are then applied, and the event is retained if $P(\chi^2_{\mathrm{fit}}) > 0.10$. It is required that at least one $\pi^+\pi^-$ pair has a mass within 0.02 GeV/c^2 of the K_S^0 mass.

The events

$$J/\psi \to \phi K^{\pm} K_S^0 \pi^{\mp} \to \pi^+ \pi^- K^{\pm} \pi^+ \pi^- \pi^{\mp}$$

[Reaction (4), subset (c)] are selected by one-constraint kinematic fits with the assumption that a K_L^0 is missing in the event. The event is retained if $P(\chi^2_{\mathrm{fit}}) > 0.05$. To select $J/\psi \to K_L^0 K_S^0 K^{\pm} K_S^0 \pi^{\mp}$ events it is required that at least one of the six possible $(\pi^+\pi^-)(\pi^+\pi^-)$ pairings has both $\pi^+\pi^-$ masses within 0.02 GeV/c^2 of the K_S^0 mass, and that at least one $\pi^+\pi^-$ pair has a detached vertex.

Figures 3(a) and 3(b) show the K^+K^- invariant-mass distributions from Reaction (3) and subsets (a) and (b) of Reaction (4). The $K_S^0 K_L^0$ mass distribution

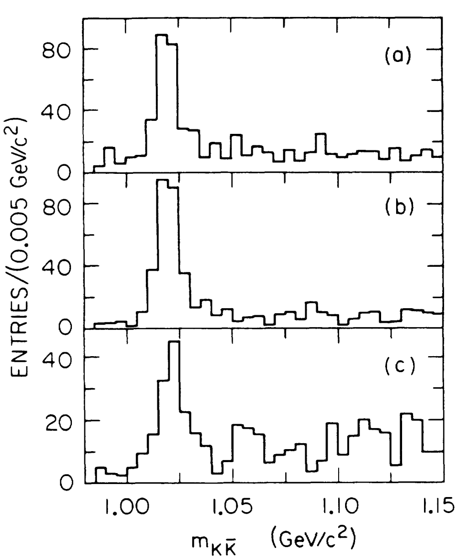

FIG. 3. K^+K^- invariant-mass distribution (a) from $J/\psi \to K^+ K^- K^+ K^- \pi^0$, and (b) from $J/\psi \to K^+ K^- K^{\pm} K_S^0 \pi^{\mp}$, with (a) four and (b) two possible entries per event; (c) $K_S^0 K_L^0$ invariant-mass distribution from $J/\psi \to K_S^0 K_L^0 K^{\pm} K_S^0 \pi^{\mp}$ with up to six entries per event. Background from events not containing K_S^0's is subtracted in (b) and (c).

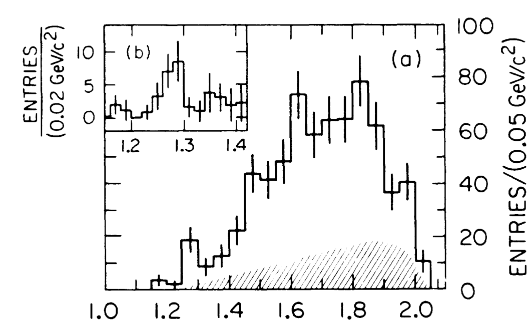

FIG. 4. (a) Summed $K^+K^-\pi^0$ and $K^{\pm} K_S^0 \pi^{\mp}$ invariant-mass distributions. (b) Detail of 1.2-GeV/c^2 mass region after selection of $m(K\bar{K}) < 1.15$ GeV/c^2. The shaded area shows the estimate of the background.

from subset (c) of Reaction (4) is displayed in Fig. 3(c). Clear ϕ signals are observed. The summed $K^{\pm}K_S^0\pi^{\mp}$ and $K^+K^-\pi^0$ mass spectra, for events in which the mass of the recoiling $K\bar{K}$ system is within 0.015 GeV/c^2 of the nominal ϕ mass, is shown in Fig. 4(a). The shaded area represents the background of events not containing a ϕ, obtained from a ϕ sideband (1.075 ± 0.030 GeV/c^2). The main feature is a broad distribution following the shapes of $J/\psi \to \phi K^*K$ phase space. The K^*K dominance is confirmed by a study of the $K^{\pm}K_S^0\pi^{\mp}$ system with the background-free subsample of Reaction (4), subset (a). No enhancement in the 1.4-GeV/c^2 mass region is seen. A small signal at 1.28 GeV/c^2 is enhanced by our requiring the $K\bar{K}$ invariant mass of the $K\bar{K}\pi$ system to below 1.15 GeV/c^2 [Fig. 4(b)].

Upper limits for the production of the $f_1(1420)$ and the $\eta(1440)$ are derived from maximum-likelihood fits performed on the invariant-mass spectrum in Fig. 4(a) in the 1.35–1.60-GeV/c^2 mass region. These fits include a $J/\psi \to \phi K^*K$ phase-space distribution plus a Breit-Wigner parametrization for the resonance. The upper limits, as well as the fitted parameters of the structure at 1.28 GeV/c^2, are listed in Table I.

The detection efficiencies for Reactions (1)–(4) are obtained by the assumption of isotropic decay angular distributions for the $K\bar{K}\pi$ part,[8] with the exception of the pseudoscalar $\eta(1440)$. The deduced branching fractions are listed in Table I. An isoscalar $K\bar{K}\pi$ system is assumed in the correction for unobserved decay modes. The errors include uncertainties due to the fit procedure, event selection criteria, Monte Carlo simulation of low-energy photon showers, and flux determination.

In summary, the $J/\psi \to \omega K\bar{K}\pi$ and $J/\psi \to \phi K\bar{K}\pi$ reactions are dominated by phase-space–distributed ωK^*K and ϕK^*K intermediate states. The ratio

$$\frac{B(J/\psi \to \omega K^*\bar{K}+\text{c.c.})}{B(J/\psi \to \phi K^*\bar{K}+\text{c.c.})} = 2.7 \pm 1.0$$

is larger than expected in the SU(3)-symmetric limit (0.93).[9] We have observed an enhancement at $1.442 \pm 0.005^{+0.010}_{-0.017}$ GeV/c^2 in the $K^{\pm}K_S^0\pi^{\mp}$ and $K^+K^-\pi^0$ systems recoiling against an ω. The width of $0.024 < \Gamma < 0.084$ GeV/c^2 (90% C.L. limits) and the observed decay angular distributions are not consistent with that of the pseudoscalar $\eta(1440)$, as seen in the same experiment.[10]

No signal at the nominal $f_1(1285)$ mass is seen. The reverse pattern is observed in the $K\bar{K}\pi$ system recoiling against the ϕ. There is no indication for either $f_1(1420)$ or $\eta(1440)$ production, but a small signal at 1.28 GeV/c^2. If the observed enhancements are identified with the $f_1(1420)$ and $f_1(1280)$ mesons, quark correlations imply a nonideal mixing of the axial-vector nonet.[11]

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[1]S. J. Brodsky, T. A. Grand, R. R. Hogan, and D. G. Coyne, Phys. Lett. **73B**, 203 (1978); K. Koller and T. Walsh, Nucl. Phys. **B140**, 449 (1978). The subject of quark correlations is discussed by H. E. Haber and J. Perrier, Phys. Rev. D **32**, 2961 (1985).

[2]The new nomenclature for hadrons is adopted [M. Aguilar-Benitez (Particle Data Group), Phys. Lett. **170B**, 1 (1986)]. $\eta(1440)$, $f_1(1285)$, and $f_1(1420)$ were formerly called ι, D, and E, respectively.

[3]The $f_1(1420)$ has been studied in hadronic and $\gamma\gamma$ interactions. However, its spin and parity assignment is in dispute, with $J^P=1^+$ and 0^- seen in different experiments. $J^P=1^+$: C. Dionisi *et al.*, Nucl. Phys. **B169**, 1 (1980); T. A. Armstrong *et al.*, Phys. Lett. **146B**, 273 (1984); H. Aihara *et al.*, Phys. Rev. Lett. **57**, 2500 (1986). $J^P=0^-$: P. Baillon *et al.*, Nuovo Cimento A **50**, 393 (1967); S. U. Chung *et al.*, Phys. Rev. Lett. **55**, 779 (1985); A. Ando *et al.*, Phys. Rev. Lett. **57**, 1296 (1986); D. F. Reeves *et al.*, Phys. Rev. D **34**, 1960 (1986).

[4]D. Bernstein *et al.*, Nucl. Instrum. Methods Phys. Res. **226**, 310 (1984).

[5]Spurious showers associated with decays or interactions of charged and neutral hadrons in the shower counters are often observed.

[6]From a fit to the $K^{\pm}\pi^{\mp}$ and $K_S^0\pi^{\mp}$ mass spectra it is estimated that $(60 \pm 15)\%$ of the $J/\psi \to \omega K^{\pm}K_S^0\pi^{\mp}$ events form an ωK^*K intermediate state.

[7]A similar analysis method, applied to the $J/\psi \to \gamma 4\pi$ reaction, is described in R. M. Baltrusaitis *et al.*, Phys. Rev. D **33**, 1222 (1986).

[8]For the $J/\psi \to \omega K\bar{K}\pi$ reaction the detection efficiency is $\approx 6\%$ lower if $J^P=0^-$ is assumed for the $K\bar{K}\pi$ system.

[9]See Haber and Perrier, Ref. 1; S-wave phase space has been taken into account.

[10]See, e.g., J. D. Richman, in *Proceedings of the Twentieth Rencontre de Moriond (Hadronic Session), Les Arcs, France, 10–17 March 1985*, edited by J. Tran Thanh Van (Editions Frontiéres, Gif-sur-Yvette, France, 1985).

[11]Haber and Perrier, Ref. 1.