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Partial wave analysis of $J/\psi \rightarrow \gamma(K^{\pm}K_S^0\pi^{\mp})$ [1]

BES Collaboration

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Abstract

BES data on $J/\psi \to \gamma(K^{\pm}K_S^0\pi^{\mp})$ are presented. There is a strong peak due to $\eta(1440)/\iota$, which is fitted with a Breit–Wigner amplitude with s-dependent widths for decays to K^*K, κK, $\eta\pi\pi$ and $\rho\rho$; κ refers to the $K\pi$ S-wave. At a $K\bar{K}\pi$ mass of ~ 2040 MeV, there is a second peak with width ~ 400 MeV; $J^P = 0^-$ is preferred over 1^+ and 2^- respectively by 5.2 and 6.8 standard deviations. It is a possible candidate for a 0^- $s\bar{s}g$ hybrid partner of $\pi(1800)$.

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There have been earlier data from Mark III [1] and DM2 [2] for J/ψ radiative decays to $K^{\pm}K_S^0\pi^{\mp}$, as well as $K^+K^-\pi^0$. Recently, the BES group has published data on the latter channel [3]. Here we present BES data on decays to $K^{\pm}K_S^0\pi^{\mp}$. These data have lower backgrounds than for $K^+K^-\pi^0$, because of the identification of $K_S^0 \to \pi^+\pi^-$. Consequently, the partial wave analysis may be extended up to a $K\bar{K}\pi$ mass of 2300 MeV, covering an interesting structure at ~ 2040 MeV.

The Beijing Spectrometer(BES) has collected 7.8×10^6 J/ψ triggers, used here. Details of the detector are given in Ref. [4]. We describe briefly those detector elements playing a crucial role in the present measurement. Tracking is provided by a 10 superlayer main drift chamber (MDC). Each superlayer contains four layers of sense wires measuring both the position and the ionization energy loss ($d\mathrm{E}/dx$) of charged particles. The momentum resolution is $\sigma_P/P = 1.7\%\sqrt{1+P^2}$, where P is the momentum of charged tracks in GeV/c. The resolution of the $d\mathrm{E}/dx$ measurement is $\sim \pm 9\%$, providing good π/K separation and proton identification for momenta up to 600 MeV/c. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of 330 ps for hadrons. Outside the TOF system is an electromagnetic calorimeter made of lead sheets and streamer tubes and having a z positional resolution of 4 cm. The energy resolution scales as $\sigma_E/E = 22\%/\sqrt{E}$, where E is the energy in GeV. Outside the shower counter is a solenoidal magnet producing a 0.4 Tesla magnetic field.

Each candidate event is required to have four charged tracks. Each track must have a good helix fit in the polar angle range $-0.8 < \cos\theta < 0.8$ and a transverse momentum > 60 MeV/c. A vertex is required within an interaction region ± 30 cm longitudinally and 3 cm radially. A positive identification of just one $K^{\pm}$ is required using time of flight and/or dE/dx. Events are fitted kinematically to the 4C hypothesis $J/\psi \to \gamma(K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})$, requiring a confidence level $> 5\%$.

Backgrounds arise mainly from $\pi^{0}K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$. Those events giving a better fit to these channels are rejected. Next, we require $|U_{\text{miss}}| = |E_{\text{miss}} - P_{\text{miss}}| < 0.15$ GeV/c^2, so as to reject the events with multi-photons or more or less than one charged kaon; here, E_{miss} and P_{miss} are, respectively, the missing energy and missing momentum of all charged particles. The momentum of the $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ system transverse to the photon $P_{t\gamma}^{2} = 4|P_{\text{miss}}|^{2}\sin^{2}(\theta_{m\gamma}/2) < 0.005$ (GeV/c)^2 is required in order to remove the background $J/\psi \to \pi^{0}K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$; here $\theta_{m\gamma}$ is the angle between the missing momentum and the photon direction. Finally, K_s^0 are selected with a cut on the $\pi^{+}\pi^{-}$ invariant mass, $|M_{\pi^{+}\pi^{-}} - M_{K_s^0}| < 25$ MeV. Fig. 1(a) shows the $\pi^{+}\pi^{-}$ invariant mass closest to the K_S^0 mass before the K_s^0 are selected; a very strong signal K_S^0 is seen. The number of surviving events is 1095 with 57 ± 5 non-K_S^0 background under the K_S^0. For our final fit, we use 683 events below a $K\bar{K}\pi$ mass of 2.3 GeV. A constraint to the K_S^0 vertex does not improve the signal/background ratio further, but loses some events.

The effects of the various selection cuts on the data is simulated with a full Monte Carlo of the BES detector including the decay path of the K_s^0; 250,000 Monte Carlo events are successfully fitted to $J/\psi \to \gamma(K^{\pm}K_S^0\pi^{\mp})$. All background reactions are similarly fitted to this channel. The estimated background is $29 \pm 7\%$, mostly from $J/\psi \to \pi^{0}(K^{\pm}K_S^0\pi^{\mp})$, some from non-$K_S^0$ events. It peaks at about 2.3 GeV, and follows phase space closely. We have included it in the amplitude analysis, but it has little effect, since all genuine signals have a characteristic dependence on either or both of production and decay angles.

Fig. 1(b) shows the $K^{\pm}K_S^0\pi^{\mp}$ mass spectrum; the dark histogram shows the estimated background in the analysis region. There is a conspicuous and somewhat asymmetric peak due to $\eta(1440)/\iota$, similar to the earlier data from Mark III, DM2 and BES. At high mass, there is a distinct peak at 2040 MeV. Fig. 2 shows Dalitz plots for three mass ranges: (a) 1360-1560 MeV, (b) 1600–1750 MeV, and (c) 1800–2200 MeV; fits are shown in (d), (e) and (f). There is a conspicuous $K^{*}K$ decay mode in the first region of the $\eta(1440)$. At higher masses, it disappears rapidly, and the mass projections shown in Fig. 3 are consistent with decays to κK only; above 1560 MeV, there is no significant evidence for $a_0(980)K$, $a_0 \to K\bar{K}$.

We have carried out a partial wave analysis using amplitudes constructed from Lorentz-invariant combinations of the 4-vectors and the photon polarization for J/ψ initial states with helicity ± 1. Cross sections are summed over photon polarisations. The relative magnitudes and phases of the amplitudes are determined by a maximum likelihood fit. We include $K\bar{K}\pi$ states with quantum numbers 0^-, 1^+, 2^- and 2^+. There are two helicity amplitudes for 1^+, three for 2^- and three for 2^+. Because production is via an electromagnetic transition, the same phase is used for different helicity amplitudes to the same final

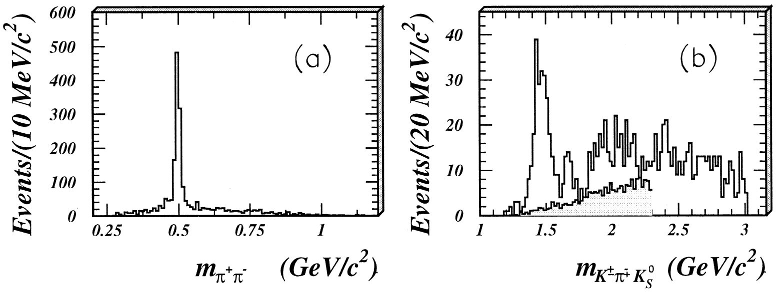

Fig. 1. (a) the $\pi^{+}\pi^{-}$ invariant mass with invariant mass closest to the K_S^0 mass; (b) $K\bar{K}\pi$ mass spectrum. The dark dashed histogram of (b) shows the estimated background in the analysis region ($K\bar{K}\pi$ mass below 2.3 GeV).

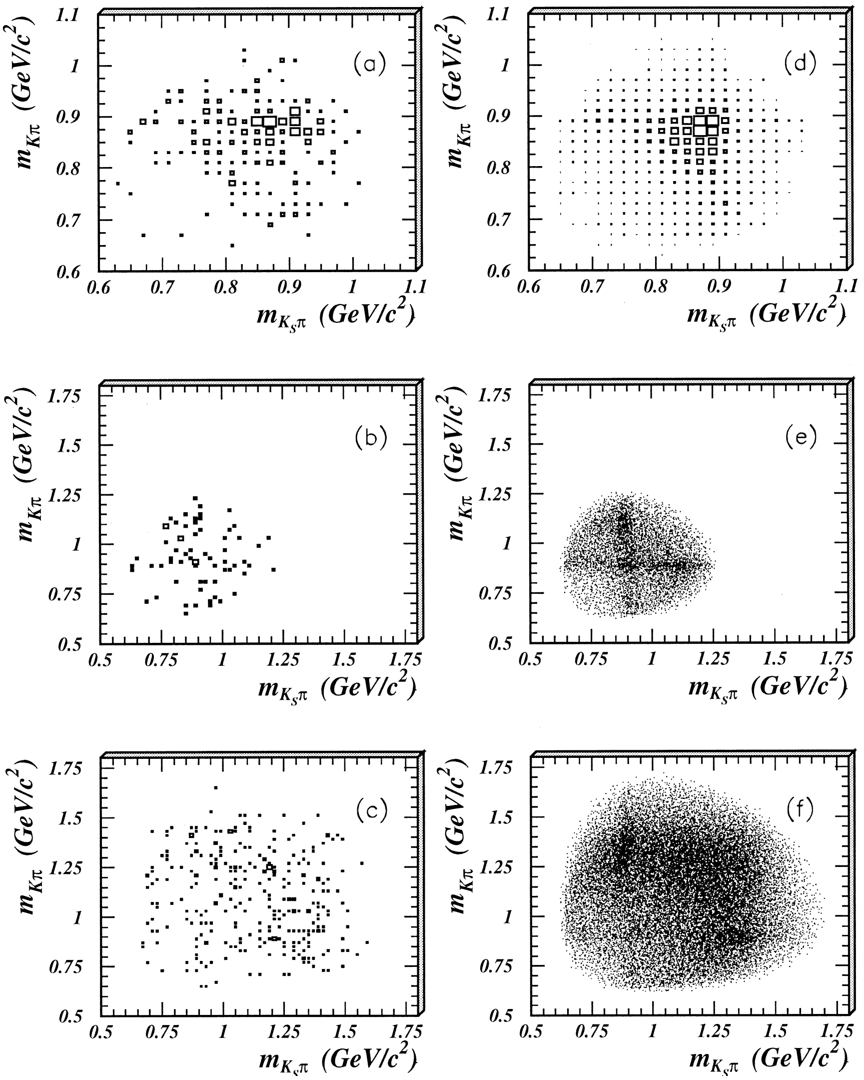

Fig. 2. Dalitz plots for $KK\pi$ mass ranges (a) 1360–1560 MeV, (b) 1600–1750 MeV, (c) 1800–2200 MeV; (d), (e) and (f) show fitted Dalitz plots.

state. Different phases are allowed for different decay channels, e.g K^*K and κK, because of strong interaction effects due to rescattering.

The analysis is discussed separately for the mass region of $\eta(1440)$ and the 2040 MeV peak. The $\eta(1440)$ has been fitted using a Breit–Wigner amplitude with s-dependent width:

$$f = \frac{\Lambda}{M^2 - s - iM\left[\Gamma_{K^*K}(s) + \Gamma_{\eta\sigma}(s) + \Gamma_{\rho\rho}(s) + \Gamma_{\kappa K}(s)\right]}\,. \tag{1}$$

The numerator Λ is a complex coupling constant. The $\Gamma(s)$ are taken to be proportional to the available phase space for each channel, evaluated numerically [5]. The $\eta\pi\pi$ phase space is taken from $\eta\sigma$, the dominant channel, but $a_0(980)\pi$ phase space is similar and both are slowly varying over this mass region. The magnitude of each Γ is adjusted iteratively so that cross sections integrated over the resonance agree with the branching ratios determined experimentally. The magnitude of $\Gamma_{\eta\sigma}$ has been obtained from BES data on radiative decays to $\eta\pi\pi$

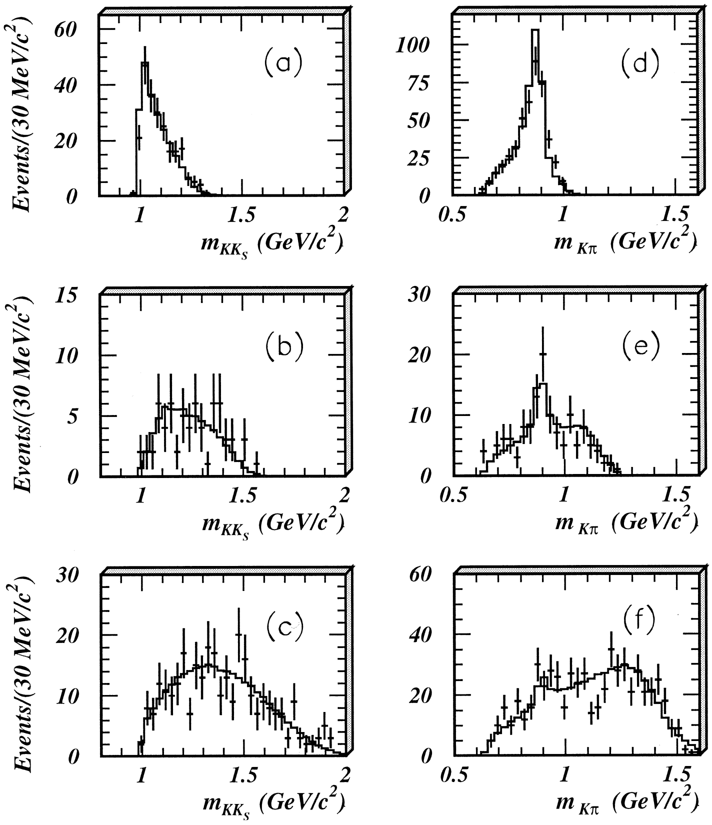

Fig. 3. Projections on to (a)–(c) $K^{\pm}K^0_S$ mass, (d)–(f) $K\pi$ mass for the three mass intervals of Fig. 2; histograms show the fit.

[6]. That for $\Gamma_{\rho\rho}$ has been obtained by fitting BES data on radiative decays to 4π [7], including in the fit $\eta(1440)$ and the broad $\eta(1800)$. Here $\eta(1800)$ refers to the very broad 0^- signal ($\Gamma \simeq 1$ GeV) derived by Bugg and Zou [8] from an analysis of several channels of J/ψ radiative decay. Values of Γ_{K^*K} and $\Gamma_{\kappa K}$ are obtained from the present data.

In the mass region of the $\eta(1440)$, half the κK signal comes from the low mass tail of $\eta(1800)$ and its constructive interference with $\eta(1440)$. That is, if $\eta(1800)$ is removed from the fit, the κK width of $\eta(1440)$ needs to be doubled. Removing the $\eta(1800)$ has a significant, but not dramatic, effect on log likelihood, which changes by 4.8 for 2 extra parameters.

The $f_1(1420)$ is also included in the amplitude analysis, and a small component due to $f_1(1285)$. Both optimise close to the masses and widths quoted by the Particle Data Group (PDG) [9], so we fix them at PDG values. The amplitude analysis distinguishes cleanly between quantum numbers 1^+ and 0^- for K^*K decays. If the whole $\eta(1440)$ signal is fitted with $J^P = 1^+$ (optimising its mass and width), log likelihood is worse by 11.4, a significant amount. (Our definition of log likelihood is such that it increases by 0.5 for a one standard deviation change in one parameter).

In the earlier analysis of BES data on the $K^+K^-\pi^0$ final state [3], a fairly large amplitude was fitted for $\eta(1800)$. The smaller background in present data and the wider mass range allow us to show that this component should in fact be rather small. Its effects on the $\eta(1440)$ may be replaced with some increase in the total width of that resonance and an increase in its width for decays to K^*K. Present results for the fitted widths are shown in Fig. 4 and

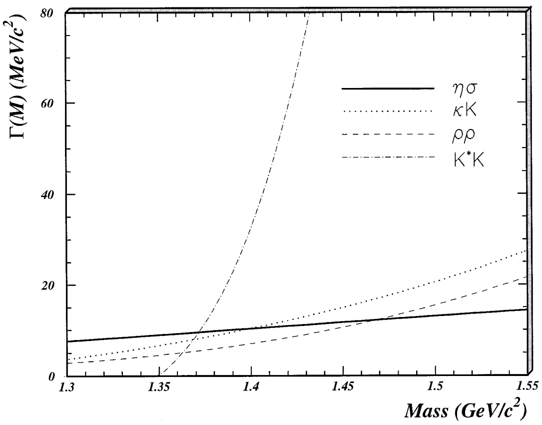

Fig. 4. The s-dependence of widths fitted to $\eta(1440)$.

branching fractions in Table 1. The fit is compared with the $K\bar{K}\pi$ mass spectrum by the histogram in Fig. 5.

A free fit to the mass gives 1440 MeV. However, $\eta\pi\pi$ data give a resonance mass of 1405 ± 5 MeV, according to the summary by the Particle Data Group [9]. The s-dependent width we use for $\eta(1440)$ explains naturally a mass difference of 20 MeV between $\eta\pi\pi$ and $K\bar{K}\pi$ data; the rapidly increasing phase space for K^*K makes the $K\bar{K}\pi$ channel peak higher and explains also the asymmetric shape of the peak, which rises rapidly on the lower side of the peak and falls more slowly on the upper side. A small ($\sim$ 15 MeV) discrepancy remains between the peaks fitted to $\eta\pi\pi$ and $K\bar{K}\pi$. We adopt a compromise between fitting these data and $\eta\pi\pi$ by using a mass of 1432 MeV, but the effect on other conclusions is negligible. Interferences between $\eta(1440)$ and the broad $\eta(1800)$ depend on their relative phases and can shift the peak in different data sets; so we do not regard this small discrepancy as a matter for concern.

Around 1650 MeV, there is some indication for a narrow $K\bar{K}\pi$ peak. However, fitting it requires an unreasonably narrow width ~ 30 MeV. An $s\bar{s}$ state at this mass has no obvious non-strange partners. If fitted, it is only a two standard deviation effect. Therefore we discard it as a statistical fluctuation. Including it has negligible effects on parameters fitted to $\eta(1440)$ and the peak at 2040 MeV.

We now turn to the latter peak. It cannot be explained by the very broad $\eta(1800)$, which has a completely different and much flatter shape, illustrated by the shaded area in Fig. 5(b) below. We fit it with a simple Breit–Wigner amplitude of constant width. Its mass and width optimise at $M = 2040 \pm 50$ MeV, $\Gamma = 400 \pm 90$ MeV. We have tried fits to this peak with resonances having quantum numbers 0^-, 1^+ and 2^-; for standard $q\bar{q}$ states, one does not expect 3^+ in kaonic channels until 2300 MeV. We find that log likelihood is better for 0^- than 1^+ by 16.4. The latter has one additional parameter, so it is a poorer fit by 5.2 standard deviations. If a combination of 0^- and 1^+ amplitudes is used, log likelihood improves only by 0.6, and the fitted 1^+ component is very small: 4.4% of 0^- in cross section. These results are not sensitive to the $\eta(1800)$ contribution: removing it, the distinction between quantum numbers 0^- and 1^+ for the 2040 MeV peak remains at a log likelihood difference of 12.9.

We have also tried adding or substituting 2^-. Alone it gives a poor fit, worse in log likelihood than 0^- by 27.9. This demonstrates that 2^- and 0^- are well separated by their distinctively different angular distributions. If it is added freely to the fit, it improves log likelihood by 3.2 for three extra parameters; this cannot be considered significant. Fig. 5 shows magnitudes of components fitted in the amplitude analysis when the 2040 MeV peak is fitted as 0^-. The slight differences between Fig. 5(b) and (d) is due to interferences of $\eta(1440)$ and $\eta(2040)$ with the broad $\eta(1800)$ in Fig. 5(b).

Branching fractions for production and decay, including the dominant interferences, are given in Table 2. Values are integrated up to a $K\bar{K}\pi$ mass of 2.3 GeV. Decays to $K^{\pm}K_S\pi^{\mp}$ have a branching ratio $1/3$ of all $K\bar{K}\pi$ decays. We correct all measured branching ratios by this factor 3, so as to quote branching fractions for all $K\bar{K}\pi$ charge states. The overall branching fraction, summed over all final states is $(6.0 \pm 0.4 \pm 2.1) \times 10^{-3}$.

Table 1
Branching ratios (BR) of $\eta(1440)$ integrated over its width

Decay channel	BR (%)
K^*K	0.70 ± 0.05
κK	0.13 ± 0.03
$\eta\pi\pi$	0.09 ± 0.03
$\rho\rho$	0.08 ± 0.03

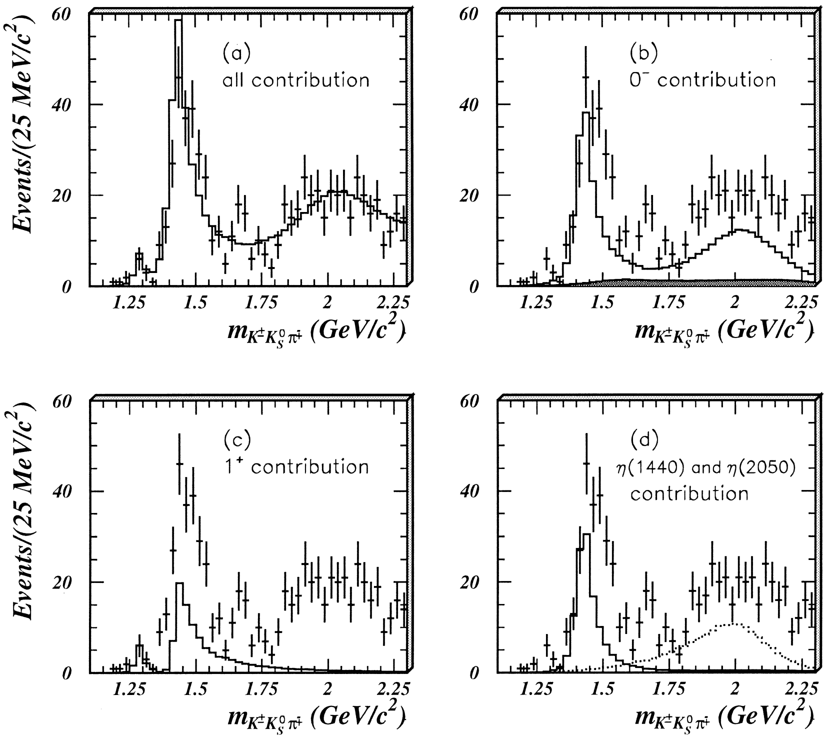

Fig. 5. Projections from all events below a $K^\pm K_S \pi^\mp$ mass of 2.3 GeV of (a) all contributions, (b) 0^- including interferences, (c) 1^+ and (d) $\eta(1440)$ (full curve) and $\eta(2040)$ (dotted) without interferences; the dark shaded histogram of (b) is the contribution of $\eta(1800)$. Crosses are data and histograms the fit.

We now discuss possible interpretations for the 2040 MeV peak. Our data for J/ψ radiative decays to $\eta\pi^+\pi^-$ [6] were fitted using an $\eta(1760)$ with a width of 250 MeV and an $\eta_2(1840)$. The $\eta(1760)$ is entirely distinct from $\eta(1800)$, which has a much larger width. A possible interpretation is that it is the $n=3$ $q\bar{q}$ state. Then the $\eta(2040)$ observed here could be its $s\bar{s}$ partner.

However, the VES collaboration has identified a $\pi(1800)$ [10] with curious decay modes to $f_0(1300)\pi$, $f_0(980)\pi$ and $K_0(1430)K$, but not $\rho\pi$. There has been speculation that this is an $I=1$ hybrid [11]. The $\eta(1760)$ would make a natural partner; its decays to $\eta\sigma$ and $a_0(980)\pi$ are to be expected for a hybrid. It is natural to expect a corresponding $s\bar{s}g$ state decaying to κK in the $K\bar{K}\pi$

Table 2
Branching fractions (BF) for production and decay. Values are corrected for all charge states in $K\bar{K}\pi$

Process	BF (%)
1) $J/\psi \to \gamma\eta(1440)$, $\eta(1440) \to K\bar{K}\pi$	$(1.66 \pm 0.10 \pm 0.58) \times 10^{-3}$
2) $J/\psi \to \gamma f_1(1285)$, $f_1(1285) \to K\bar{K}\pi$	$(0.61 \pm 0.04 \pm 0.21) \times 10^{-3}$
3) $J/\psi \to \gamma f_1(1420)$, $f_1(1420) \to K\bar{K}\pi$	$(0.68 \pm 0.04 \pm 0.24) \times 10^{-3}$
4) $J/\psi \to \gamma\eta(1800)$, $\eta(1800) \to \kappa K$	$(0.58 \pm 0.03 \pm 0.20) \times 10^{-3}$
5) Interference between (1) and (4)	$(0.15 \pm 0.01 \pm 0.05) \times 10^{-3}$
6) Interference between (1) and (3)	$(-0.03 \pm 0.01 \pm 0.01) \times 10^{-3}$
7) $J/\psi \to \gamma\eta(2040)$, $\eta(2040) \to \kappa K$	$(2.1 \pm 0.1 \pm 0.7) \times 10^{-3}$

channel roughly 200–250 MeV above the peak in $\eta\pi\pi$. In J/ψ radiative decays, the amplitude for production of $q\bar{q}$ states is suppressed by two powers of α_s, required to couple intermediate gluons to quarks; at 2040 MeV, $\alpha_s \simeq 0.41$. Production of a hybrid will only be suppressed by one power of α_s in amplitude. We therefore examine the possible interpretation of $\eta(1760)$ as a $q\bar{q}g$ hybrid.

For a hybrid, the branching fraction expected in the $K\bar{K}\pi$ channel is half that for $\eta\pi\pi$, since in J/ψ decays intermediate gluons couple equally to $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$. If fitted as 0^-, the branching ratio for the 2040 MeV peak in $K\bar{K}\pi$ is $(2.1 \pm 0.1 \pm 0.7) \times 10^{-3}$; this value is obtained after allowing for interferences with $\eta(1800)$ and includes the error in the overall normalisation. It is to be compared with the branching ratio for $\eta(1760)$ in $\eta\pi\pi$ of $(1.8 \pm 0.75) \times 10^{-3}$ [6]. These values are consistent within the sizable errors with the expectation for hybrids.

The magnitude of branching ratio we now fit to $\eta(1800) \to \kappa K$ is $(0.58 \pm 0.03 \pm 0.20) \times 10^{-3}$. Again, the error includes the overall normalisation uncertainty. It compares with $(1.08 \pm 0.45) \times 10^{-3}$ fitted to $\eta\pi\pi$ decays [6]. Within the errors, these values are now consistent with flavour-blind decays of a glueball.

In summary, present data contain less background than earlier data on $J/\psi \to \gamma(K^+K^-\pi^0)$ and allow a somewhat improved determination of the properties of $\eta(1440)$. Its dominant decay mode is to K^*K. This suggests it is the first radial excitation of $\eta(958)$, probably mixed with the broad $\eta(1800)$, in order to account for its strong production in J/ψ radiative decays. We now find a small component of $\eta(1800)$ decaying to κK.

We observe a peak at 2040 MeV which may be fitted with a 0^- resonance of width 400 MeV. $J^P = 0^-$ is preferred over 1^+ and 2^- respectively by 5.2 and 6.8 standard deviations. Its branching fraction, when compared with the $\eta\pi\pi$ channel, would be consistent with interpretation as a 0^- $s\bar{s}g$ hybrid. [2]

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