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12 November 1998

PHYSICS LETTERS B

Physics Letters B 440 (1998) 217–224

Partial wave analysis of $J/\psi \to \gamma(K^+K^-\pi^0)$ [1]

BES Collaboration

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PII: S0370-2693(98)01241-6

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Received 22 September 1998
Editor: L. Montanet

Abstract

BES data on $J/\psi \to \gamma(K^+K^-\pi^0)$ display a strong peak in the $K^+K^-\pi^0$ mass spectrum at 1450 MeV. This peak and a corresponding one in $J/\psi \to \gamma(\eta\pi^+\pi^-)$ at ~ 1400 MeV may be fitted well by $\eta(1440)$ with dominant decays to $K^*(890)K$, using an s-dependent width in the Breit-Wigner amplitude. A broad background is also required in KK_0 (where K_0 stands for the $K\pi$ S-wave) and also in $\eta\pi\pi$, but is probably not resonant in this mass range. © 1998 Published by Elsevier Science B.V. All rights reserved.

PACS: 14.40.Cs; 12.39.Mk; 13.25.Jx; 13.40.Hq

There is a long history of controversy surrounding the E/ι, called $\eta(1440)$ by the Particle Data Group (PDG) [1]. The Mark III group, in their latest publication [2], conclude that their data require 3 resonances: 1^{++} at 1443 MeV decaying to KK^*, a 0^- state at 1416 MeV decaying to $a_0(980)\pi$ and a 0^- resonance at 1490 MeV decaying to KK^*. The DM2 group [3] present quite a different picture: 1^+ at 1462 MeV decaying to KK^*, a 0^- resonance at 1459 MeV decaying to $a_0(980)\pi$, and a 0^- resonance at 1421 MeV decaying to KK^*. New results have also been obtained recently in $\bar{p}p$ annihilation. The Crystal Barrel group has observed a 0^- peak in $\eta\pi\pi$ at 1409 MeV in data on $\bar{p}p \to \eta\pi^+\pi^-\pi^0\pi^0$ at rest [4] and a 0^- peak at 1400–1415 MeV in data on $\bar{p}p \to \eta\pi^0\pi^0\pi^0$ at rest [5]. The Obelix group has studied $\bar{p}p \to (K^\pm K_S\pi^\mp)\pi^+\pi^-$ at rest [6,7]; they observe a $K\bar{K}\pi$ peak at ~ 1410 MeV, but conclude that it contains two 0^- resonances, one at 1416 MeV decaying mostly to KK_0 and a broader one at 1465 MeV decaying mostly to KK^*. Thus most of the evidence now points to a 0^- state in the range 1400-1420 MeV, but there is confusion about what happens at higher masses. We present new BES data from J/ψ radiative decays. They help clarify the picture at the higher masses.

The BES data, like earlier data from Mark III and DM2, display a strong but asymmetric $K^+K^-\pi^0$ peak at ~ 1450 MeV. We shall show that these data and our data on J/ψ radiative decays to $\eta\pi^+\pi^-$ [8] can be interpreted in terms of a single 0^- resonance having decays to $\eta\pi\pi$ and KK_0 but also a strong decay to $KK^*(890)$; a proper treatment of the rapidly rising phase space for this last channel is a crucial ingredient in the analysis. A broad interfering 0^- background is also required.

This analysis is based on a sample of $8.6 \times 10^6 J/\psi$ data acquired in the BES detector at the BEPC storage ring of the Institute of High Energy Physics in Beijing. The salient features of the detector are (i) a 40-layer main cylindrical drift chamber (MDC) for measurement of charged particle trajectories, momenta and dE/dx, (ii) a 48-scintillation counter time-of-flight(TOF) system for particle identification, and (iii) a 24-layer barrel electromagnetic shower counter(BSC), composed of streamer tubes and lead absorbers, with good electron-hadron separation and good detection efficiency for low-energy photons. These are all situated in a 0.4 T solenoidal magnetic field. Momentum resolution for charged tracks is $1.7\%\sqrt{1+p^2}$ GeV. The directions and energies of hard γ-rays are determined in the BSC with angular and energy resolutions of $\sigma_\phi \simeq 7.9$ mrad, $\sigma_z = 3.6$ cm and $\sigma_E/E = 0.22/\sqrt{E(\mathrm{GeV})}$, respectively. Tracks with $|\cos\theta| < 0.75$ traverse all 40 layers of the MDC and are well contained in the TOF and BSC detectors. The details

[1] Data analyzed were taken prior to the participation of UK members of the BES Collaboration.
[2] Deceased.

of the BES detector are described in Ref. [9]. The particle momentum measurements and identification assignments are further refined by applying four-constraint kinematic fits.

The event selection leads to 410 events in the $K^+K^-\pi^0$ mass range up to 1.8 GeV, corresponding to a branching ratio of $(1.7 \pm 0.25) \times 10^{-3}$ of all J/ψ decays. For this mass range, invariant mass spectra for $K^+K^-\pi^0$, $K^\pm\pi^0$ and K^+K^- combinations are shown in Fig. 1(a)–(c), together with the results of a maximum likelihood fit described below.

The Dalitz plot is shown in Fig. 2(a)–(c) for several ranges of $K^+K^-\pi^0$ mass. Fig. 2(d) also shows the result of the fit. For masses in the peak region of Fig. 2(a), 1.4–1.5 GeV, the conspicuous feature of the Dalitz plot is a clustering at the intersection of the two K^* bands. This feature is less conspicuous for higher $K\bar{K}\pi$ masses.

We shall interpret these data using a maximum likelihood fit based on $\eta(1440)$ and $\eta(1800)$ decaying to $[KK_0]_{\ell=0}$, $[KK^*]_{\ell=1}$, $[a_0(980)\pi]_{\ell=0}$ and $f_1(1420) \to [KK^*]_{\ell=0}$. Here $\eta(1800)$ is a very broad background, which has been fitted previously [10] to J/ψ radiative decays to $\rho\rho$, $\omega\omega$, $K^*\bar{K}^*$ and $\phi\phi$. The value of ℓ is the orbital angular momentum in the decay of $\eta(1440)$, $\eta(1800)$ or $f_1(1420)$. In the $J/\psi \to \gamma X$ process, the photon has orbital angular momentum $L = 1$ for decays to $\eta(1400)$ and $\eta(1800)$ and $L = 0$ or 2 for decays to $f_1(1420)$. Angular distributions for $L = 0$ and $L = 2$ decays of $f_1(1420)$ are identical except for a form factor, so we retain only $L = 0$. The amplitudes in the partial wave analysis are constructed from Lorentz-invariant combinations of the momenta and the photon polarization 4-vectors for J/ψ initial states with helicity ± 1. Cross sections are summed over photon polarizations.

For $\eta(1440)$ we use a Breit-Wigner amplitude with s-dependent width (s = mass squared):

$$f_i = \frac{\Lambda_i}{M^2 - s - iM\sum_i \Gamma_i(s)}, \qquad (1)$$

where i runs over channels $a_0(980)\pi$, KK_0 and KK^*. For $\eta(1440)$ we find that coupling constants Λ_i may be taken to have the same phase for KK_0 and KK^* decays. However in general coupling constants need to be complex, since final state interactions amongst strongly interacting particles are capable of giving each channel a separate phase, e.g. through the multiple scattering series involving rescatterings of decay products of $\eta(1440)$ through

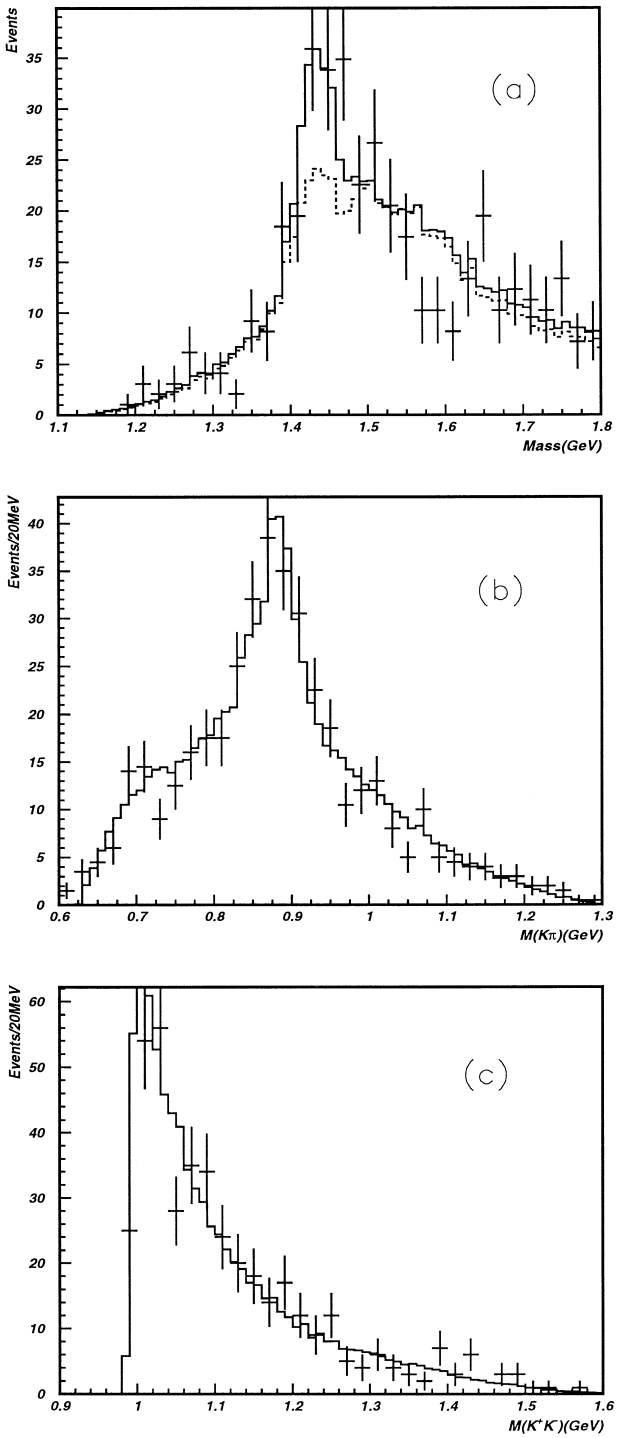

Fig. 1. Mass spectra for (a) $K^+K^-\pi^0$, (b) $K^\pm\pi^0$ and (c) K^+K^-. Full histograms show the fit reported here. The dashed histogram in (a) shows a fit without $\eta(1440) \to KK^*$.

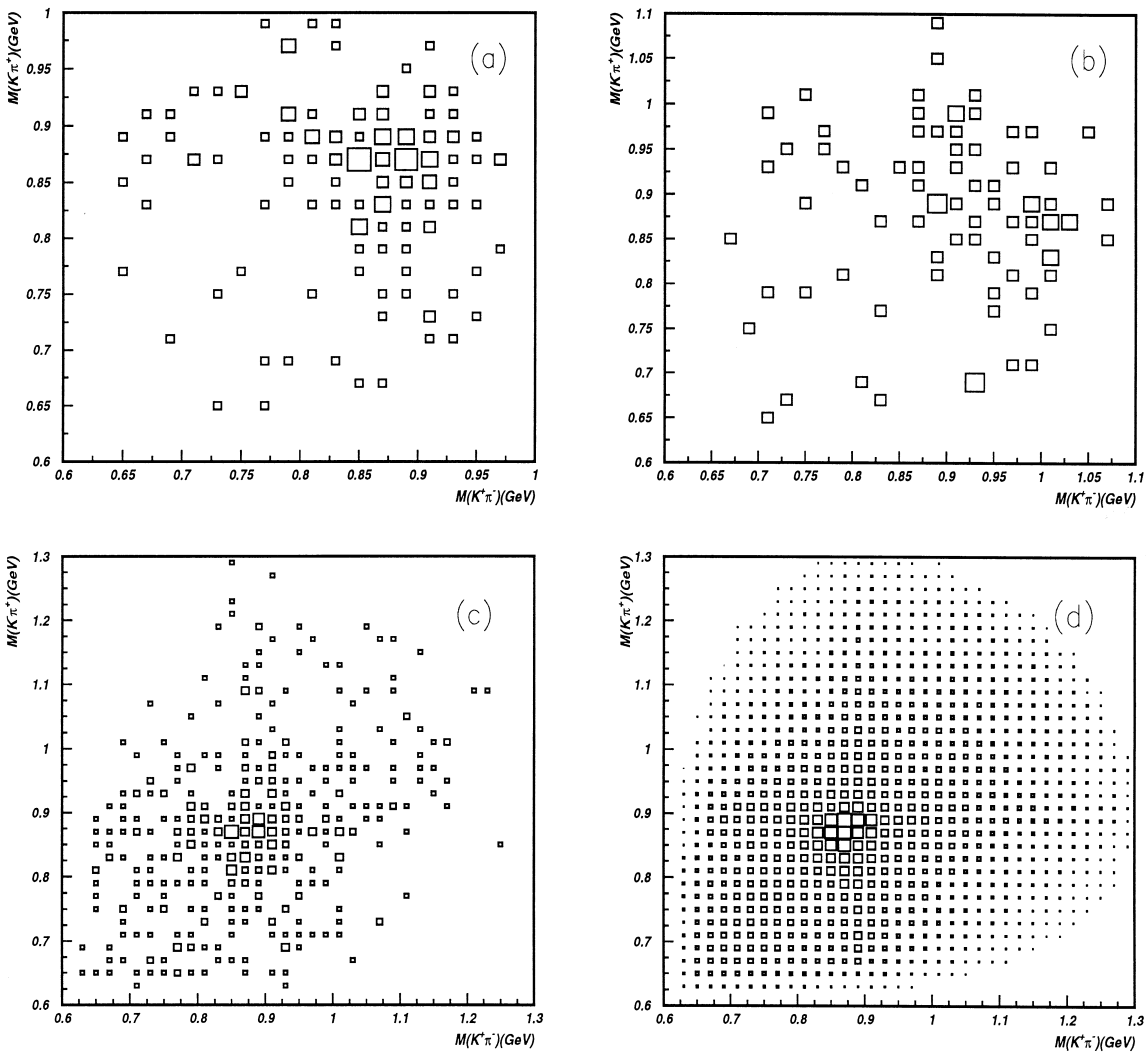

Fig. 2. Dalitz plots for $K^+K^-\pi^0$ masses in the ranges (a) 1.4–1.5 GeV, (b) 1.5–1.6 GeV, (c) 1.1–1.8 GeV; (d) shows the fitted Dalitz plot for masses in the range 1.1–1.8 GeV.

$\eta(1800)$ and vice versa. We need complex coupling constants for the background $\eta(1800)$.

The value of $\Gamma(s)$ is calculated from 3-body phase space, weighted by final-state interactions, such as that of the σ through $f_{\pi\pi}(s)$. In the case of KK^*, interferences between the two K^* bands are included. The $a_0(980)\pi$ phase space is very close to $\eta\sigma$ over this mass range, so we approximate it by $\eta\sigma$ for simplicity. For $\eta(1800)$ further decays to $\rho\rho$, $\omega\omega$, $K^*\bar{K}^*$ and $\phi\phi$ are taken from Ref. [10]. For $\eta(1440)$, our fitted values of $\Gamma_i(s)$ are shown, absolutely normalized, in Fig. 3(a). For decays to KK^*, the threshold at ~ 1385 MeV and the $\ell = 1$ centrifugal barrier give rise to a very rapid variation of Γ with s. This plays a crucial role. It has three effects. Firstly, the rapid rise in Γ_{KK^*} has the effect of cutting off decays to $\eta\pi\pi$ and KK_0 above their peaks at 1400-1415 MeV. Secondly it shifts the KK^* peak to higher masses, ~ 1440 MeV. Thirdly, it contributes to the asymmetry of the $K^+K^-\pi^0$ peak of Fig. 1(a), because of the expanding KK^* phase space above resonance.

Before discussing details of the fit, we draw attention to some striking facts about branching ratios of $\eta(1440)$ to $\eta\pi\pi$ and $K\bar{K}\pi$. These will play an important role in our interpretation. For $\bar{p}p \to \eta(1440)\sigma$, $\eta(1440) \to K\bar{K}\pi$, the first observations of E/ι by Baillon et al. [11] found a branching ratio of $(2.0 \pm 0.2) \times 10^{-3}$. If one allows for all charge states, Obelix results [7] lead to a value 2.7×10^{-3}.

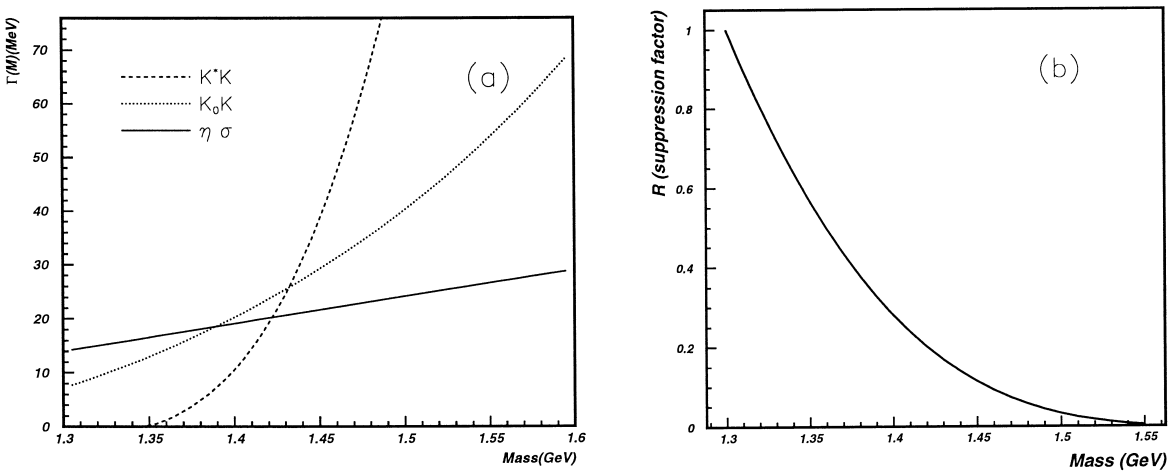

Fig. 3. (a) Variation of Γ with $M(K^+K^-\pi^0)$; (b) the suppression factor for $\bar{p}p \to X\sigma$ versus the mass of X, and normalized to its value at 1.3 GeV.

For $\bar{p}p \to \eta(1440)\sigma$, $\eta(1440) \to \eta\pi\pi$, Crystal Barrel [4] quote a branching ratio $(3.3 \pm 1.0) \times 10^{-3}$. Averaging the Obelix result with that of Baillon et al., we deduce a ratio

$$BR(K\bar{K}\pi)/BR(\eta\pi\pi) = 0.71 \pm 0.19. \quad (2)$$

However, it has been pointed out to us by members of the Crystal Barrel group [12] that the analyses in these papers did not consider interference between $\eta(1440)$ and the background $\eta(1800)$. Further work, as yet unpublished, demonstrates that this interference may reduce the branching ratio of $\eta(1440)$ to $\eta\pi\pi$ by a factor 2. Its effect on the $K\bar{K}\pi$ branching ratio is not known at present, but is probably smaller, since the broad background is smaller in $K\bar{K}\pi$ and particularly small in $\bar{p}p$ annihilation. We shall assume a value for the ratio in Eq. (2) in the range 0.7–1.4, though the precise value is not critical.

The important point is that in J/ψ decays the ratio is much larger. From our own data, allowing for all charge states, the ratio for events in the $K\bar{K}\pi$ and $\eta\pi\pi$ peaks is 10.7 ± 2. In $\eta\pi\pi$, we estimate 60 events in the $\eta\pi^+\pi^-$ peak and in $K^+K^-\pi^0 \sim 160$ above a smooth background. Factors correcting for other charge states are 1.5 and 6 respectively; the latter assumes dominance by KK_0 and/or KK^*. The DM2 and Mark III groups do not give a ratio for actual data. They analyzed their data into resonances and give the branching ratios of these resonances. If we ignore interferences, DM2 give a result for $K\bar{K}\pi/\eta\pi\pi$ of 8.3 to 13.8, depending on which of their fits we consider. Mark III results lead to a ratio of 7.5 if one ignores interferences. Lack of knowledge of the interferences clearly introduces some uncertainty, but the basic point is that J/ψ data and annihilation data differ by roughly a factor 10; an understanding of this discrepancy is required.

The first point concerning this issue is that in $\bar{p}p \to \eta(1440)\sigma$, the phase space available to the σ is limited; furthermore the σ amplitude $f_{\pi\pi}$ for $\pi\pi$ elastic scattering peaks strongly at ~ 800 MeV and approaches zero near the $\pi\pi$ threshold. The result is a strong suppression of the upper side of the $\eta(1440)$. We have done a model calculation for this suppression factor R from the formula

$$R = \int_{4\mu^2}^{(W-m_\eta)^2} ds \frac{q}{\sqrt{s}} |f_{\pi\pi}(s)|^2. \quad (3)$$

Here W is the total center of mass energy, q the momentum of η in the $p\bar{p}$ c.m. frame, μ the mass of the pion, m_η the mass of the η and s is mass squared for the σ. The result, normalized arbitrarily to its value at 1300 MeV, is shown in Fig. 3(b). Between 1400 MeV and 1465 MeV, the suppression increases by a factor 3.3. It will weaken the $\eta(1440) \to KK^*$ in $\bar{p}p$ annihilation. This suppression is absent in J/ψ decays.

In fitting BES data we find the following qualitative features. The region of intersection of the two K^* bands on Fig. 2(a) is strongly populated. The amplitude for each KK^* band has a $\cos\theta$ dependence, where θ is the decay angle with respect to the

direction of the $\eta(1440)$. This leads to a linear variation of amplitude along each K^* band. As the mass of the $K\bar{K}\pi$ system increases, the intersection point of the K^* bands crosses the edge of the Dalitz plot at a $K\bar{K}\pi$ mass of 1435 MeV. This corresponds to $|\cos\theta| = 1$. In the absence of other components, there should be a peak at the other end of the K^* bands, where $\cos\theta$ has the opposite sign. However, we find that the K^* signal there is smaller than a quarter of that where the K^* bands intersect. This requires interference with some other component: constructive at the crossing of the two bands and destructive at the opposite end of each K^* band. We find this additional component to be mostly KK_0, which varies only slowly over the Dalitz plot. We take the parameters of K_0 from a fit to LASS data [13].

The fit is made directly to BES $K^+K^-\pi^0$ data using the s-dependent form of Eq. (1). The same form is fitted separately to BES $\eta\pi^+\pi^-$ data. In addition, it is fitted to projections of Crystal Barrel and Obelix data as a check that they are at least approximately consistent with our fit. We find that the peak of $\eta(1440)$ naturally appears higher in mass in $K\bar{K}\pi \to K\bar{K}\pi$ than in $\eta\pi\pi \to \eta\pi\pi$ by ~ 25 MeV, because of the expanding KK^* phase space. The fit to each set of data on J/ψ decays or $\bar{p}p$ annihilations depends on interferences between $\eta(1440)$ and $\eta(1800)$ which move the peak position of $\eta(1440)$ by amounts up to 20 MeV. As a result, the peak in $J/\psi \to \gamma(K\bar{K}\pi)$ appears $\sim$ 40 MeV above that in $J/\psi \to \gamma(\eta\pi\pi)$.

Our fitted Dalitz plot is shown in Fig. 2(d), and the magnitudes of individual contributions from $\eta(1440)$, $\eta(1800)$ and $f_1(1420)$ are compared with data in Fig. 4. There are some interferences which are not shown. A scan of the mass of the $f_1(1420)$ component gives an optimum at 1431 ± 5 MeV. This agrees within errors with the mass given by the PDG, so we adopt PDG values for its mass and width, in order to minimize errors from this source. There are no indications of a further 1^+ signal at higher mass, for example around 1510 MeV, where the PDG quotes evidence for a second 1^+ resonance.

For $\eta(1440)$, the fitted value of M in the Breit-Wigner amplitude of Eq. (1) is 1442 ± 10 MeV. Because of the s-dependence of the width Γ, the peak in $\eta\pi\pi$ occurs at 1415 MeV, but is then shifted significantly by interference with the broad background $\eta(1800)$. The pole position is at $1.429 - i0.033$ GeV.

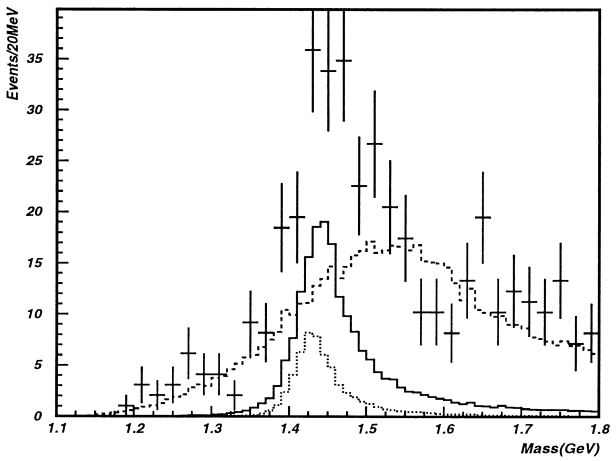

Fig. 4. Comparison with data of contributions from $\eta(1440)$ (full histogram), $\eta(1800)$ (dashed) and $f_1(1420)$ (dotted).

There is just a hint of additional structure at 1510 MeV in 0^-, but fitting an additional narrow resonance there produces only a small improvement in log likelihood, insufficient to believe such structure is beyond statistics.

Table 1 gives the percentage contributions from all channels in the fit integrated from 1.1 to 1.8 GeV. Decays of $\eta(1440)$ to KK^* dominate over decays to KK_0 by a factor 2.8. Decays of $\eta(1800)$ to KK_0 dominate strongly over those to KK^*. Fig. 4 displays the fact that the background from $\eta(1800)$ has a broad maximum around 1540 MeV. The reason for this is that the large decay width of $\eta(1800)$ to $\rho\rho$ cuts off the decay to KK_0 near the $\rho\rho$ threshold.

In several earlier papers a strong decay of $\eta(1440)$ to $a_0(980)\pi$ has been claimed. However, that result appears questionable. The most recent Crystal Barrel results [5] find decays to $a_0(980)\pi$ and $\eta\sigma$ to be in the ratio $0.4 \pm 0.2 : 1$. Our own work [8] finds a ratio 0.5 ± 0.2. The $\eta(1440)$ signal in our $\eta\pi\pi$ data is small compared with $K\bar{K}\pi$. From fits to $a_0(980)$ with a Flatté form [14], one calculates $BR[a_0(980) \to K\bar{K}]/BR[a_0(980) \to \eta\sigma] = 0.22$. This results in a negligible contribution to $K\bar{K}\pi$, consistent with the Obelix observation that KK_0 decays of $\eta(1440)$ dominate over decays via $a_0(980)\pi$; we therefore omit it. However, the broad background in $\eta\pi\pi$ due to $\eta(1800)$ is quite large, and we find that decays

Table 1
Percentage contributions from all channels in the fit, and changes in log likelihood when each component is omitted and others are re-optimized

Process	%	Δ(log likelihood)
$\eta(1440) \to K K^*$	15.9	14
$\eta(1440) \to K K_0$	5.8	6
$\eta(1800) \to K K^*$	2.2	5
$\eta(1800) \to K K_0$	53.6	50
$\eta(1800) \to a_0(980)\pi$	15.9	16
$f_1(1420) \to K K^*$	6.6	11

$\eta(1800) \to a_0(980)\pi \to K\bar{K}\pi$ make a contribution which noticebly improves the fit (by 16 in log likelihood). If both $\eta(1440)$ and $\eta(1800)$ are allowed to decay freely to $a_0(980)\pi$, the fit becomes unstable; both become unreasonably large and they swallow the $\eta(1440) \to K K_0$ decay, but with only a small change (~ 3) in log likelihood. The existence of this type of instability was noted by DM2, and we confirm their account of the instability. It disappears when only $\eta(1800)$ is allowed to decay to $a_0(980)\pi$.

Obelix claim the existence of a separate 0^- resonance at 1465 MeV decaying to $K K^*$. However, their amplitude analysis used Breit Wigner amplitudes with constant widths. We suggest their $\eta(1465)$ might be fitted by $\eta(1440)$ if one includes the strong s-dependence of the width of the $K K^*$ channel. We have tried fits to our data using two separate resonances with the masses and widths Obelix quote and have varied these masses and widths by several times their errors. There is no improvement in fitting our data over the fit we report here. We also note that the width quoted by Obelix for $\eta(1465)$ is close to what one would calculate from their width for $\eta(1416)$ and the s-dependence shown in Fig. 3(a).

The last column of Table 1 lists the changes in log likelihood when each channel is omitted from the fit. Our definition is such that a change in log likelihood of 0.5 corresponds to one standard deviation for one degree of freedom. The change in log likelihood when $\eta(1800)$ is removed is large. The change in log likelihood when $\eta(1440)$ is removed is much smaller, since $\eta(1800)$ can substitute to some degree in fitting the present data. However, the appearance of the fit is then poor, particularly the projection on to $M(K^+K^-\pi^0)$; this is shown by the dashed histogram on Fig. 1(a). Both $\eta(1800)$ and $\eta(1440)$ are definitely needed in order to account for the large difference in branching ratio $K\bar{K}\pi/\eta\pi\pi$ between J/ψ data and annihilation data. If either is omitted, one cannot account for more than a factor 3 difference between J/ψ data and annihilation data; but with both one can account for a factor ~ 10. The $\eta(1800) \to K K_0$ component is a crucial addition in accounting for this large factor. For $\eta(1440)$ we find branching ratios to $K K^*$, $K K_0$ and $\eta\pi\pi$ in the ratios 1.92 :0.83 :1, integrated over the resonance.

We conclude with one technical remark. The fit reported here is in terms of interfering amplitudes. We have also investigated a K-matrix fit. If data were available on free scattering between $\eta\sigma$, $K K^*$, $K K_0$ and other channels, the constraint of unitarity implied by the K-matrix would be useful. However, it is subject to possible problems arising from other poorly known decays, e.g. $\eta(1440) \to a_0(980)\pi$ and possible non-resonant backgrounds, which can have a strong influence on the constraint of unitarity. For both J/ψ decays and $\bar{p}p$ annihilation, the requirement is that the pole of the T-matrix should be the same in all channels; the fitted amplitudes are far below the unitarity limits for these processes. We have constructed a K-matrix solution with only minor changes in parameters from that given here. However, it is far less transparent and the numerical convergence of the fit is very much poorer than the parametrization in terms of Breit-Wigner amplitudes.

In summary, BES data on both $\eta\pi\pi$ and $K^+K^-\pi^0$ decays of $\eta(1440)$ may be fitted well with a Breit-Wigner amplitude for a 0^- resonance of mass 1442 ± 10 MeV, but with a very strong s-dependence in decays to $K K^*$. The fit also requires the presence of $f_1(1420) \to K K^*$ and a broad component $\eta(1800)$ decaying to $K K_0$.

Acknowledgements

We thank the Crystal Barrel collaboration for helpful discussions and information on branching ratios. The BES group acknowledges the staff of IHEP for technical support in running the experiment. We also thank financial support from the Royal Society for collaboration between Chinese and UK groups. This project was partly supported by China Postdoctoral Science Foundation and the Na-

tional Natural Science Foundation of China under Contract No. 19605007. The work of the BES Collaboration was supported in part by the Chinese Academy of Sciences under contract No. KJ85 (IHEP)

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