Partial Wave Analysis of $J/\psi \to \gamma(\eta\pi^+\pi^-)$

BES Collaboration
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Abstract

A partial wave analysis of BES $J/\psi \to \gamma(\eta\pi^+\pi^-)$ data has been performed in the mass region 1.1 to 2.0 GeV. A peak is observed due to $\eta(1440)$ in the $\eta\pi^+\pi^-$ invariant mass distribution; $J^P = 0^-$ is preferred over 1^+. Its mass is $M = 1385 \pm 7$ MeV and it decays into both $\eta\sigma$ and $a_0(980)\pi$, with $BR[a_0(980)\pi,\ a_0 \to \eta\pi/\eta\sigma] = 0.7 \pm 0.12(stat) \pm 0.20(syst)$. Destructive interference between the two decay modes is observed. In addition, in the higher $\eta\pi^+\pi^-$ mass region, there is a definite 2^{-+} signal, with $M = 1840 \pm 15$ MeV and $\Gamma = 170 \pm 40$ MeV and an additional 0^{-+} signal at 1760 ± 35 MeV. We also find a possible contribution from a 1^{++} signal decaying dominantly through $a_0(980)\pi$; its mass and width are fitted to be $M = 1505 \pm 20$ MeV and $\Gamma = 130^{+50}_{-20}$ MeV.

Radiative J/ψ decays provide a good laboratory for the study of glueballs and hybrids, especially in the mass range 1 to 2 GeV. Candidates have been observed in $\eta\pi^+\pi^-$, $K\overline{K}\pi$ and 4π channels. The $J/\psi \to \gamma(\eta\pi^+\pi^-)$ channel is an interesting one to study, especially in the 1400 MeV region, where $\eta(1440)$ has been found. Mark III and DM2 Collaborations made PWA analyses on this channel in 1992 [1, 2]. They focused only on the low part of the $\eta\pi^+\pi^-$ invariant mass spectrum, and both observed a narrow signal near 1400 MeV decaying mainly through $a_0(980)\pi$. Mark III claimed it to be a pseudoscalar state, while DM2 preferred but not firmly a 1^{++} spin-parity assignment. The discrepancy might be explained to some extent by the different treatment of the $\pi\pi$ $S-$wave interaction involved in the PWA. Mark III used the amplitude of Ref [3] for the $\pi\pi$ $S-$wave interaction, whereas DM2 simply ignored it. In the last few years, the understanding of the $\pi\pi$ $S-$wave has improved [4] and that parametrization is used here. The existence of a broad $f_0(400 \sim 1200)$ is now well established [5].

In order to clarify the spin-parity of the signal near 1.4 GeV, BES has restudied the decay $J/\psi \to \gamma(\eta\pi^+\pi^-)$. In our analysis we include the $\eta\sigma$ amplitude as well as the $a_0(980)\pi$, where σ is shorthand for the entire $\pi\pi$ $S-$wave amplitude. Our analysis is conducted up to $\eta\pi\pi$ masses of 2.0 GeV.

The analysis in this paper uses 8.6×10^6 J/ψ triggers collected by the Beijing Spectrometer(BES). The BES detector has been described in detail in Ref [6]. Here we only briefly describe detector elements crucial to this 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 about 9% for hadron tracks. This provides good π/K separation and proton identification in the low momentum region. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of $330ps$ for hadrons. Outside the TOF system is an electromagnetic calorimeter composed of streamer tubes and lead blocks with 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. Beyond the shower counter is a solenoidal magnet producing a 0.4 Tesla magnetic field in the central tracking region of the detector.

The η is detected here in its $\gamma\gamma$ decay mode. Therefore, much effort has been devoted to the selection of the events in the $3\gamma\pi^+\pi^-$ final state. Each candidate event is required to have two oppositely charged tracks with a good helix fit in the polar angle range $-0.8 < \cos\theta < 0.8$ and at least 3 reconstructed γ's in the barrel shower counter. A minimum energy cut of 80 MeV is imposed on the photons. Showers associated with charged tracks are also removed. Events are fitted kinematically to the 4C hypotheses $J/\psi \to 3\gamma\pi^+\pi^-$. If the number of the selected photons is larger than three, the fit is repeated using all permutations of the photons. For events with a good fit, the three photon combination with the largest probability is selected. Meanwhile, the events are also fitted to $J/\psi \to 2\gamma\pi^+\pi^-$ and $4\gamma\pi^+\pi^-$. We require

$$\chi^2(2\gamma\pi^+\pi^-) > 20, \quad \chi^2(4\gamma\pi^+\pi^-) > 20$$

to reject the $\omega\pi$, $\omega\pi\pi$ and $\rho\pi$ backgrounds. In order to suppress further the backgrounds with a π^0, a 5C fit is performed on the selected events. The extra constraint is that of the η mass. $\chi^2_{5C} < 15$ is required. This 5C fit helps improve the mass resolution for combinations of charged particles. The $\pi^+\pi^-$ and $\eta\pi^\pm$ mass distributions from the decay $J/\psi \to \gamma(\eta\pi^+\pi^-)$ are shown in Figs. 1 (a) and (b), together with the fit. Crosses denote the real data, and the full line the maximum likelihood fit.

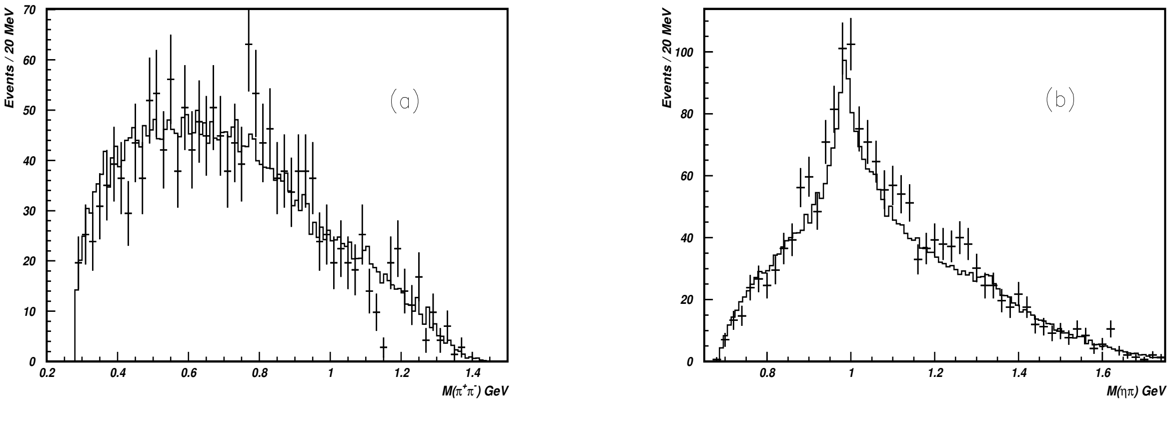

Figure 1: Mass spectra for (a) $\pi^+\pi^-$, (b) $\eta\pi^\mp$

The amplitudes in the PWA 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. The relative magnitudes and phases of the amplitudes are determined by a maximum likelihood fit to the data. Based on the study of $\pi^+\pi^-$ and $\eta\pi^\pm$ invariant mass distributions in our data, the decay chain $J/\psi \to \gamma(\eta\pi\pi)$

is analyzed taking into account the $\eta\sigma$, $a_0(980)\pi$, $\eta f_2(1270)$ and $a_2(1320)\pi$ intermediate processes. The $\eta f_2(1270)$ and $a_2(1320)\pi$ amplitudes are only used to fit the data in the high mass region. The background under the η signal is $\sim$ 30% in the 4C fit. We have included a phase space background in the PWA fit to allow for this; it agrees with what is observed experimentally in sidebands outside the η peak. It peaks strongly at high masses, and does not influence much the region below 2 GeV. All possible spin-parity assignments up to $J = 2$ have been tried. We shall use L to denote the orbital angular momentum between the photon and $\eta\pi\pi$ states in the production reaction. Because this is an electromagnetic transition, the same phase is used for amplitudes with different L but otherwise the same final state, e.g. $f_1(1285) \to a_0\pi$; different phases are allowed for decays of one resonance to different channels, e. g. $f_1(1285) \to a_0\pi$ and $\eta\sigma$.

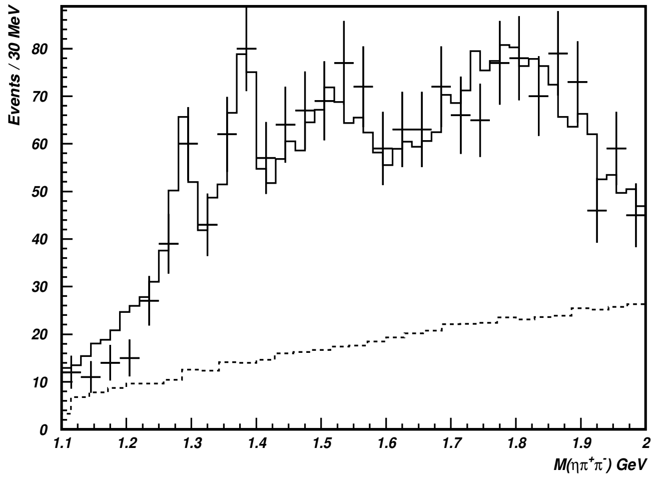

Figure 2: The $\eta\pi^+\pi^-$ mass spectrum

We now discuss the features of the data and the outcome of fits. The $\eta\pi^+\pi^-$ mass projection fitted to the real data is shown in Fig. 2, where the dashed line represents the fitted background. There are narrow peaks in the $\eta\pi\pi$ mass spectrum at 1285 and 1400 MeV and a further possible peak at $\sim$ 1505 MeV. Parameters of the Particle Data Group (PDG) are used for $f_1(1285)$. The data favor $J^{PC} = 1^{++}$ over 0^{-+}. For the 1^{++} assignment, log likelihood, $log\ L$, improves by 11.8 when $f_1(1285)$ is included using two $L = 0$ amplitudes with $f_1(1285) \to a_0(980)\pi$ or $\eta\sigma$. (Our definition of $log\ L$ is such that a change of 0.5 corresponds to 1σ). The dominant process is decay of $f_1(1285)$ to $a_0(980)\pi$. With our 4 fitted parameters, the statistical significance of the peak is 3.9σ. The inclusion of $L = 2$ amplitudes affects log likelihood very little ($\Delta(log\ L) < 1.0$). A fit with $J^{PC} = 0^{-+}$ instead gives ln L worse by 6.6 than for 1^{++}.

The peak at $\sim$ 1400 MeV optimizes at $M = 1385 \pm 7$ MeV as shown in Fig. 3(a). This is consistent with recent determinations cited by the PDG. We fix $\Gamma = 45$ MeV from recent results of the Crystal Barrel collaboration [7]. Our data demand a similar narrow width, but are less accurate. The fit prefers 0^{-+} over 1^{++}. $Log\ L$ improves by 16.6 for 0^{-+} using 4 fitted parameters, a 4.7σ effect; 1^{++} instead gives $\Delta(log\ L)$ = 5.8 for 4 fitted parameters. The resonance decays through both $\eta\sigma$ and $a_0(980)\pi$ modes, and the $\eta\sigma$ decay dominates. The ratio of the decay branching fractions is

$$\frac{BR[\eta(1440) \to a_0\pi,\ a_0 \to \eta\pi]}{BR[\eta(1440) \to \eta\sigma]} = 0.70 \pm 0.12.$$

The systematic error (dependent on which amplitudes are included in the fit) is $\sim \pm 0.20$. The two decay modes interfere destructively.

At $\sim$ 1505 MeV, there is a further wider peak. This is just the mass at which a narrow 1^{++} resonance decaying to KK^* is reported in the Particle Data Tables. We have included a 1^{++} resonance and $log\ L$ improves by 19.8 for 4 fitted parameters, a 5.4σ effect. The mass is fitted to be $M = 1505 \pm 20$ MeV. However, our data require a broader width, $\Gamma = 130^{+50}_{-20}$ MeV as shown in Fig. 3(c). The decay to $\eta\sigma$ is roughly half of that to $a_0\pi$ in strength. We have tried alternative fits with $J^P = 0^-$, 2^+ and 2^- but the improvement in $log\ L$ is < 8.0.

Now we comment on the broad components. Underneath the narrow peaks in Fig. 2 is a broad 0^- contribution shown in Fig. 4(a). It gives an improvement in $log\ L$ of 31.3 for 4 fitted parameters. It is parametrized according to the formula developed by Bugg and Zou [8] to fit data on $J/\psi \to \gamma(4\pi)$ and we shall refer to it as $\eta(1800)$. This broad component falls away above $\sim$ 1500 MeV because of suppression caused by strong decays to $\rho\rho$, $\omega\omega$ and $K^*\overline{K}^*$.

A large improvement to the fit is given by including a $J^{PC} = 2^{-+}$ resonance, which optimizes at $M = 1840 \pm 15$ MeV, $\Gamma = 170 \pm 40$ MeV, as shown by scans in Figs. 3(d) and (e). The production process is with $L = 1$. We find branching fractions to $f_2(1270)\eta$, $a_2(1320)\pi$ and $\eta\sigma$ in the ratios 4 : 1 : 2. The improvement in $log\ L$ is 50.6 for a fit to 3 complex coupling constants, mass and width; this is an 8.1σ effect. Earlier, Crystal Ball [9], CELLO [10] and Crystal Barrel [11] have reported evidence for a 2^{-+} resonance in $\eta\pi\pi$ at $\sim$ 1875 MeV. It is possible that this accounts for the resonance we observe. We have tried $J^P = 2^+$ instead of 2^-, but the fit is much worse.

The Crystal Barrel group also reports an $\eta_2(1645)$. We find an insignificant improvement of 2.4 in $log\ L$ with 5 fitted parameters when this is included. We do, however, find an improvement of 36.5 in $log\ L$ (7.2σ) using a 0^- resonance at 1760 ± 35 MeV, produced with $L = 0$; in this case, only 4 fitted parameters are needed. Its decays to $a_0\pi$ and $\eta\sigma$ are in the ratio 1: 0.57. Its width is large, $\sim$ 250 MeV, but not well determined.

The branching ratio for $J/\psi \to \gamma(\eta\pi^+\pi^-)$ for $\eta\pi\pi$ masses up to 2 GeV is $(3.4 \pm 0.43) \times 10^{-3}$. Branching ratios for individual components are summarized in Table 3. The errors cover not only statistics, but also systematic errors dependent on which components are included in the fit.

In summary, we find evidence for narrow peaks due to the presence of $f_1(1285)$ and $\eta(1440)$. There is a definite requirement for a 2^- component at $M = 1840 \pm 15$ MeV with $\Gamma = 170 \pm 40$ MeV and strong evidence for a 0^{-+} component around 1760 MeV, though its width is not well determined. In addition, a large contribution to our fit is also observed from a broad $f_1(1505)$.

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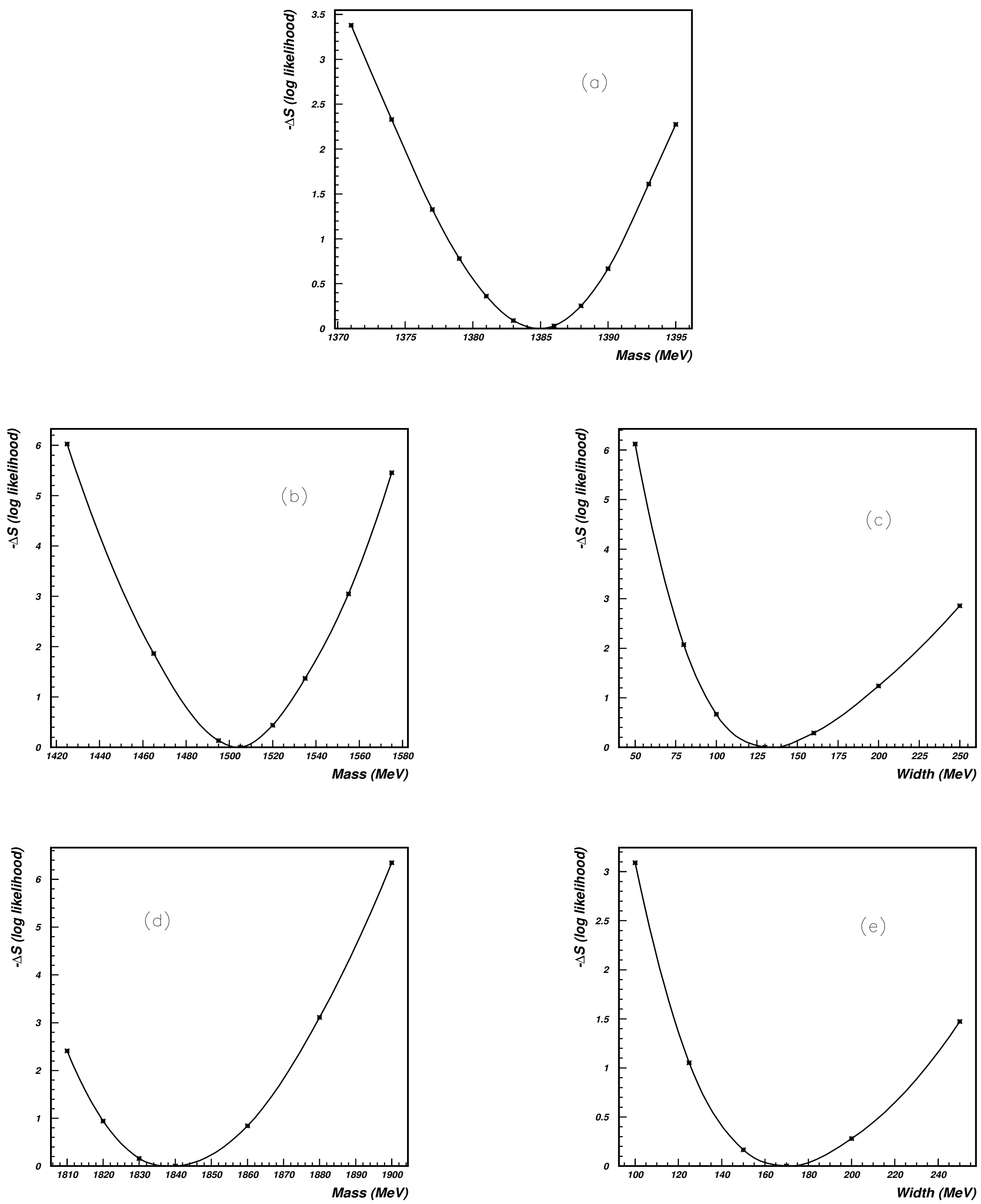

Figure 3: Scans for (a)the mass of $\eta(1440)$, (b)the mass of $f_1(1505)$, (c)the width of $f_1(1505)$, (d)the mass of $\eta_2(1840)$ and (e)the width of $\eta_2(1840)$

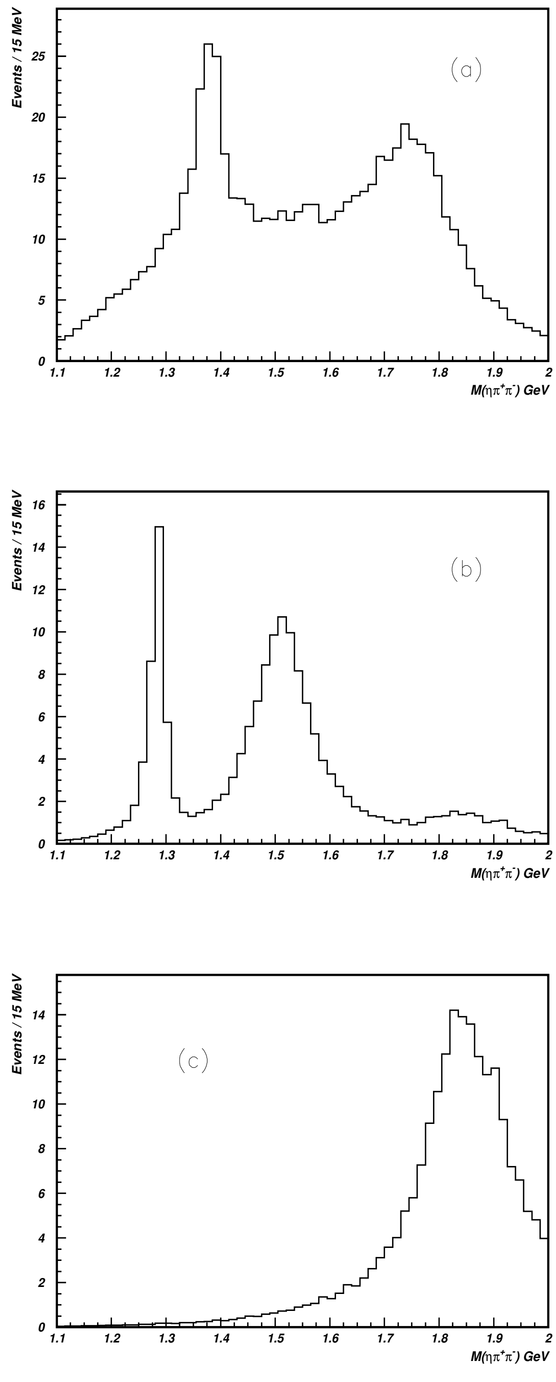

Figure 4: Component contributions from (a) 0^-, (b) 1^+ and (c) 2^-

Table 1: Product branching ratios for the resonances in $J/\psi \to \gamma\eta\pi^+\pi^-$ decays. Errors are assessed from systematic variations over a variety of fits. There is a $\pm$ 15% uncertainty in overall normalization arising from uncertainties in the net number of J/ψ data and the event selection.

Process	Branching ratios
$BR(J/\psi \to \gamma f_1(1285)) \times BR(f_1(1285) \to \eta\pi^+\pi^-)$	$(1.5 \pm 0.3) \times 10^{-4}$
$BR(J/\psi \to \gamma\eta(1440)) \times BR(\eta(1440) \to \eta\pi^+\pi^-)$	$(2.6 \pm 0.7) \times 10^{-4}$
$BR(J/\psi \to \gamma f_1(1505)) \times BR(f_1(1505) \to \eta\pi^+\pi^-)$	$(4.5 \pm 1.0) \times 10^{-4}$
$BR(J/\psi \to \gamma\eta(1800)) \times BR(\eta(1800) \to \eta\pi^+\pi^-)$	$(7.2 \pm 0.3) \times 10^{-4}$
$BR(J/\psi \to \gamma\eta_2(1840)) \times BR(\eta_2(1840) \to \eta\pi^+\pi^-)$	$(6.2 \pm 2.2) \times 10^{-4}$
$BR(J/\psi \to \gamma\eta(1760)) \times BR(\eta(1760) \to \eta\pi^+\pi^-)$	$(1.2 \pm 0.5) \times 10^{-3}$

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