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New hadronic states observed at BES II

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Abstract. The report includes the new observation of $X(1835)$ in $J/\psi \to \gamma\eta'\pi^+\pi^-$, the $\omega\phi$ threshold enhancement in $J/\psi \to \gamma\omega\phi$, the $\omega\omega$ structure in $J/\psi \to \gamma\omega\omega$ and the broad 1^{--} structure at the low K^+K^- invariant-mass spectrum in $J/\psi \to K^+K^-\pi^0$.

PACS. 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 13.25.Gv Decays of J/ψ, Υ, and other quarkonia

1 Introduction

BES [1] is a large general purpose solenoidal detector at Beijing Electron Positron Collider (BEPC). The 5.8×10^7 J/ψ events were accumulated with BES II, which provides a good laboratory for the search of new hadronic states. All the results presented here are based on this data sample.

2 Observation of X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$

An anomalous enhancement near the mass threshold in the $p\bar{p}$ invariant-mass spectrum from $J/\psi \to \gamma p\bar{p}$ decays was reported by the BES II experiment [2]. This enhancement was fitted with a sub-threshold $\mathcal{S}$-wave Breit-Wigner (BW) resonance function with a mass $M = 1859^{+3+5}_{-10-25}\,\mathrm{MeV}/c^2$, a width $\Gamma < 30\,\mathrm{MeV}/c^2$ (at the 90% C.L.) and a product branching fraction $B(J/\psi \to \gamma X) \cdot B(X \to p\bar{p}) = (7.0 \pm 0.4^{+1.9}_{-0.8}) \times 10^{-5}$. Among various theoretical interpretations [3–8] of the $p\bar{p}$ mass threshold enhancement, the most intriguing one is that of a $p\bar{p}$ bound state, sometimes called baryonium [3,6,9], which has been the subject of many experimental searches [10]. The baryonium interpretation of the $p\bar{p}$ mass enhancement requires a new resonance with a mass around $1.85\,\mathrm{GeV}/c^2$ and it would be supported by the observation of the resonance in other decay channels. $\pi^+\pi^-\eta'$ [5,6] is a possible decay mode for a $p\bar{p}$ bound state.

The analysis of $J/\psi \to \gamma\eta'\pi^+\pi^-$ is described in detail in ref. [11]. Two decay modes of η' ($\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$ and $\eta' \to \gamma\rho$) are used in the analysis. The combined $\pi^+\pi^-\eta'$ spectrum for the two decay modes of η' is fitted with a BW function convolved with a Gaussian mass resolution function ($\sigma = 13\,\mathrm{MeV}/c^2$) to represent the $X(1835)$ signal plus a smooth polynomial background function. The mass and width obtained from the fit (shown in the bottom panel of fig. 1) are $M = 1833.7 \pm 6.1\,\mathrm{MeV}/c^2$ and $\Gamma = 67.7 \pm 20.3\,\mathrm{MeV}/c^2$. The signal yield from the fit is 264 ± 54 events with a confidence level 45.5% (χ^2/d.o.f. = 57.6/57) and $-2\ln\mathcal{L} = 58.4$. A fit to the mass spectrum without BW signal function returns $-2\ln\mathcal{L} = 126.5$. The change

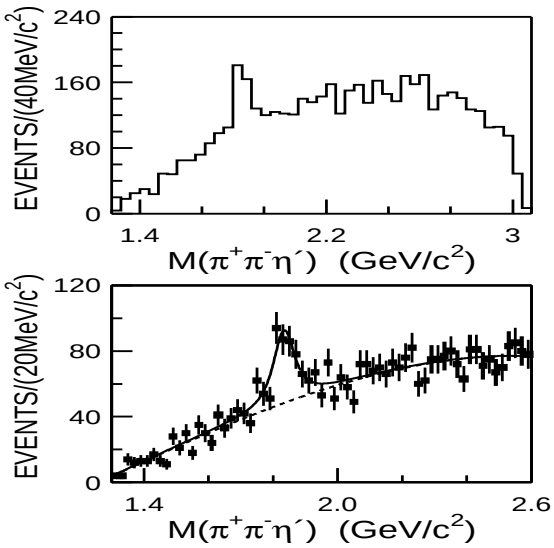

Fig. 1. The $\pi^+\pi^-\eta'$ invariant-mass distribution for selected events from both the $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$) and $J/\psi \to \gamma\eta'\pi^+\pi^-$ ($\eta' \to \gamma\rho$) analyses. The bottom panel shows the fit (solid curve) to the data (points with error bars); the dashed curve indicates the background function.

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in $-2\ln\mathcal{L}$ with Δ(d.o.f) = 3 corresponds to a statistical significance of 7.7 σ for the signal.

Using MC-determined selection efficiencies of 3.72% and 4.85% for the $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \gamma\rho$ modes, respectively, we determine a product BF of

$$B(J/\psi \to \gamma X) \cdot B(X \to \pi^+\pi^-\eta') = (2.2 \pm 0.4) \times 10^{-4}.$$

The mass and width of the $X(1835)$ are not compatible with any known meson resonance [12]. We examined the possibility that the $X(1835)$ is responsible for the $p\bar{p}$ mass threshold enhancement observed in radiative $J/\psi \to \gamma p\bar{p}$ decay [2]. It has been pointed out that the $\mathcal{S}$-wave BW function used for the fit in ref. [2] should be modified to include the effect of final-state interactions (FSI) on the shape of the $p\bar{p}$ mass spectrum [7,8]. Redoing the $\mathcal{S}$-wave BW fit to the $p\bar{p}$ invariant-mass spectrum in ref. [2] including the zero isospin, $\mathcal{S}$-wave FSI factor of ref. [8], yields a mass $M = 1831 \pm 7\,\mathrm{MeV}/c^2$ and a width $\Gamma < 153\,\mathrm{MeV}/c^2$ (at the 90% C.L.); these values are in good agreement with the mass and width of $X(1835)$ reported here. Moreover, according to ref. [6], the $\pi\pi\eta'$ mode is expected to be strong for a $p\bar{p}$ bound state. Thus, the $X(1835)$-resonance is a prime candidate for the source of the $p\bar{p}$ mass threshold enhancement in $J/\psi \to \gamma p\bar{p}$ process. In this case, the J^{PC} and I^G of the $X(1835)$ could only be 0^{-+} and 0^+, which can be tested in future experiments. Also in this context, the relative $p\bar{p}$ decay strength is quite strong: $B(X \to p\bar{p})/B(X \to \pi^+\pi^-\eta') \sim 1/3$ (The product BF determined from the fit that includes FSI effects on the $p\bar{p}$ mass spectrum is within the systematic errors of the result report in ref. [2]). Since decays to $p\bar{p}$ are kinematically allowed only for a small portion of the high-mass tail of the resonance and have very limited phase space, the large $p\bar{p}$ branching fraction implies an unusually strong coupling to $p\bar{p}$, as expected for a $p\bar{p}$ bound state [9,13]. However, other possible interpretations of the $X(1835)$ that have no relation to the $p\bar{p}$ mass threshold enhancement are not excluded.

3 Observation of the $\omega\phi$ threshold enhancement in $J/\psi \to \gamma\omega\phi$

Systems of two vector particles have been intensively studied for signatures of gluonic bound states. The radiative J/ψ decay $J/\psi \to \gamma\omega\phi$ is a double Okubo-Zweig-Iizuka (OZI) suppressed process, the measurement of this decay and the search for possible resonance states will provide useful information on two vector-meson systems. MARK III Collaboration [14] studied $J/\psi \to \gamma\omega\phi$ decays, but did not find clear structures in the $\omega\phi$ invariant-mass spectrum. The final states of $\omega\phi$ are also observed in photon-photon collisions by ARGUS [15,16] experiment and the cross-sections were measured [16].

The detailed analysis of $J/\psi \to \gamma\omega\phi$ is described in ref. [17]. The decay modes of $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-$ are used in the analysis. Since the decays of $J/\psi \to \omega\phi$ and $J/\psi \to \omega\phi\pi^0$ are forbidden by C invariance, the 294 observed $\omega\phi$ events present direct evidence

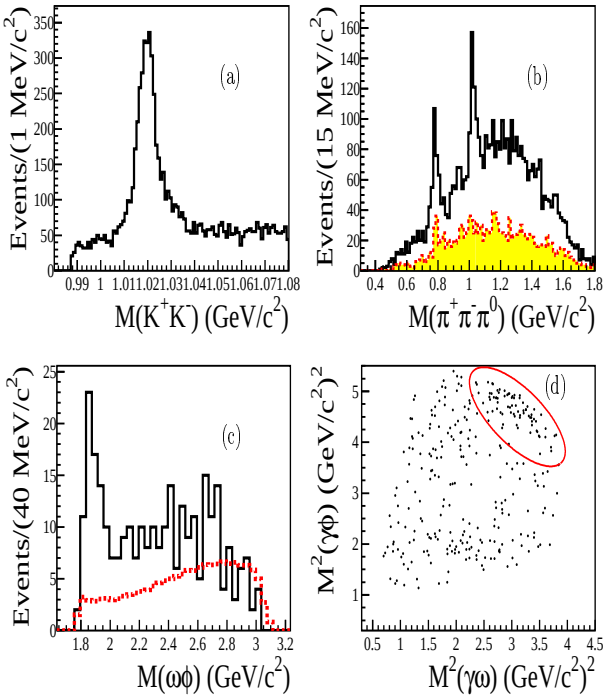

Fig. 2. (a) The K^+K^- invariant-mass distribution. (b) The $\pi^+\pi^-\pi^0$ invariant-mass distribution; the open histogram is for candidate events with $m_{K^+K^-}$ being in the ϕ range, and the shaded histogram is for events with $m_{K^+K^-}$ being in the ϕ sideband region. (c) The $K^+K^-\pi^+\pi^-\pi^0$ invariant-mass distribution for the $J/\psi \to \gamma\omega\phi$ candidate events. The dashed curve indicates the acceptance varying with the $\omega\phi$ invariant mass. (d) Dalitz plot.

for the radiative $J/\psi \to \gamma\omega\phi$ decay. The histogram in fig. 2(c) shows the $K^+K^-\pi^+\pi^-\pi^0$ invariant-mass distribution for events with $|m_{K^+K^-} - m_\phi| < 15\,\mathrm{MeV}/c^2$ and $|m_{\pi^+\pi^-\pi^0} - m_\omega| < 30\,\mathrm{MeV}/c^2$, and a structure peaked near the $\omega\phi$ threshold is observed. The dashed curve in the figure indicates how the acceptance varies with invariant mass. The peak is also evident as a diagonal band along the upper right-hand edge of the Dalitz plot in fig. 2(d). No evidence of an enhancement near the $\omega\phi$ threshold is observed from the sideband events of ω and ϕ. And the study from inclusive and exclusive MC shows that the $\omega\phi$ threshold enhancement is not from backgrounds.

The significance of the $\omega\phi$ threshold enhancement is more than 10σ. From a partial-wave analysis with covariant helicity coupling amplitudes, a spin-parity of $X = 0^{++}$ with an $\mathcal{S}$-wave $\omega\phi$ system is favored. The mass and width of the enhancement are determined to be $M = 1812^{+19}_{-26}$ (stat) $\pm$ 18 (syst) MeV/c^2 and $\Gamma = 105 \pm 20$ (stat) $\pm$ 28 (syst) MeV/c^2, and the product branching fraction is $\mathcal{B}(J/\psi \to \gamma X) \cdot \mathcal{B}(X \to \omega\phi) = (2.61 \pm 0.27\ (\mathrm{stat}) \pm 0.65\ (\mathrm{syst})) \times 10^{-4}$. The mass and width of this state are not compatible with any known scalars listed in the Particle Data Group (PDG) [12]. It could be an unconventional state [18–22]. However, more statistics and further studies are needed to clarify this.

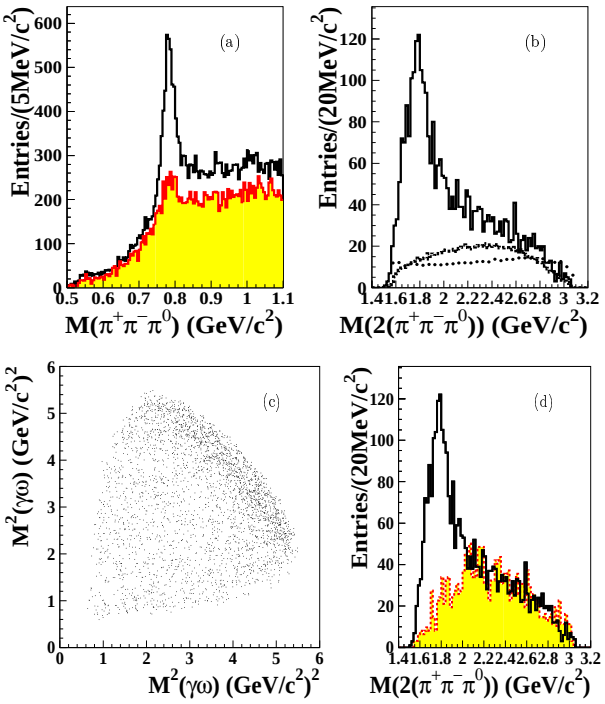

Fig. 3. (a) The $\pi^+\pi^-\pi^0$ mass distribution for the best $\omega\omega$ combination after the requirement that the invariant mass of the other $\pi^+\pi^-\pi^0$ is inside the ω region (open histogram), defined by $|m_{\pi^+\pi^-\pi^0} - m_\omega| < 40\,\mathrm{MeV}/c^2$, or in the sideband range (shaded histogram), defined by $40\,\mathrm{MeV}/c^2 < |m_{\pi^+\pi^-\pi^0} - m_\omega| < 80\,\mathrm{MeV}/c^2$. (b) The $2(\pi^+\pi^-\pi^0)$ invariant-mass distribution for candidate events. The dashed curve is the phase space invariant-mass distribution, and the dotted curve shows the acceptance *versus* the $\omega\omega$ invariant mass. (c) The Dalitz plot. (d) The $2(\pi^+\pi^-\pi^0)$ invariant mass of the inclusive Monte Carlo sample (shaded histogram).

4 Pseudoscalar production at the $\omega\omega$ threshold in $J/\psi \to \gamma\omega\omega$

The $\eta(1760)$ was reported by the MARK III Collaboration in J/ψ radiative decays and was found to decay to $\omega\omega$ [23] and $\rho\rho$ [24]. It was also observed by the DM2 [25, 26] and BES I [27]. The $\eta(1760)$ was suggested to be a 3^1S_0 pseudoscalar $q\bar{q}$ meson, but some authors suggest a mixture of glueball and $q\bar{q}$ or a hybrid [28,29]. In our analysis of $J/\psi \to \gamma\omega\omega$ ($\omega \to \pi^+\pi^-\pi^0$) [30], the presence of a signal around $1.76\,\mathrm{GeV}/c^2$ and its pseudoscalar character are confirmed, and the mass, width, and branching fraction are measured by partial-wave analysis.

The histogram of fig. 3(b) shows the $2(\pi^+\pi^-\pi^0)$ invariant-mass distribution of events with both $\pi^+\pi^-\pi^0$ masses within the ω range ($|m_{\pi^+\pi^-\pi^0} - m_\omega| < 40\,\mathrm{MeV}/c^2$). There are 3046 events with a clear peak at $1.76\,\mathrm{GeV}/c^2$. The phase space invariant-mass distribution and the acceptance *versus* $\omega\omega$ invariant mass are also shown in the figure. The corresponding Dalitz plot is shown in fig. 3(c). The shaded histogram of fig. 3(d) shows the $2(\pi^+\pi^-\pi^0)$ invariant-mass distribution of the inclusive sample. There is no peak at the $\omega\omega$ mass threshold in the invariant-mass distribution at around $1.76\,\mathrm{GeV}/c^2$. The fitting of fig. 3(d) yields 1441 ± 50 background events within the $\omega\omega$ invariant-mass range from $1.6\,\mathrm{GeV}/c^2$ to $2.8\,\mathrm{GeV}/c^2$.

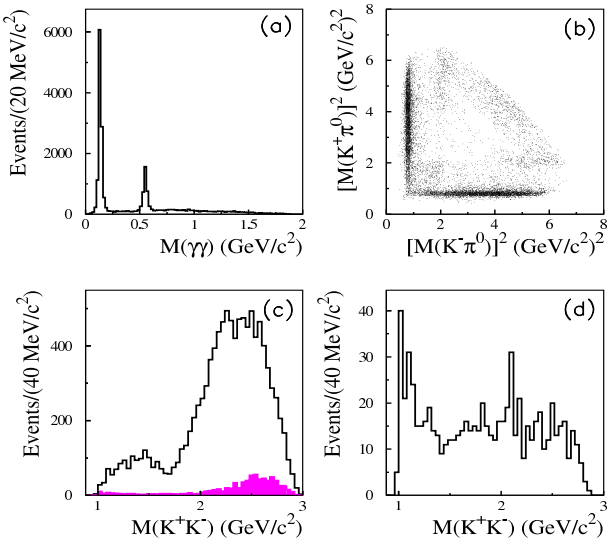

Fig. 4. (a) The $\gamma\gamma$ invariant-mass distribution. (b) The Dalitz plot for $K^+K^-\pi^0$ candidate events. (c) The K^+K^- invariant-mass distribution for $K^+K^-\pi^0$ candidate events; the solid histogram is data and the shaded histogram is the background (normalized to data). (d) The K^+K^- invariant-mass distribution for the π^0 mass sideband events (not normalized).

The partial-wave analysis shows that the structure around $1.76\,\mathrm{GeV}/c^2$ in the $\omega\omega$ invariant-mass spectrum is predominantly pseudoscalar, with small contributions from $f_0(1710)$, $f_2(1640)$, and $f_2(1910)$. The mass of the pseudoscalar is $M = 1744 \pm 10$ (stat) ± 15 (syst) MeV/c^2, the width $\Gamma = 244^{+24}_{-21}$ (stat) ± 25 (syst) MeV/c^2, and the product branching fraction is $\mathrm{Br}(J/\psi \to \gamma\eta(1760)) \cdot \mathrm{Br}(\eta(1760) \to \omega\omega) = (1.98 \pm 0.08\ (\mathrm{stat}) \pm 0.32\ (\mathrm{syst})) \times 10^{-3}$.

5 Observation of a broad 1^{--} resonant structure in the K^+K^- mass spectrum in $J/\psi \to K^+K^-\pi^0$

A broad peak is observed at low K^+K^- invariant mass in $J/\psi \to K^+K^-\pi^0$ decays, detailed analysis is described in ref. [31]. The Dalitz plot for the selected 10631 events is shown in fig. 4(b), where a broad K^+K^- band is evident in addition to the $K^*(892)$ and $K^*(1410)$ signals. This band corresponds to the broad peak observed around $1.5\,\mathrm{GeV}/c^2$ in the K^+K^- invariant mass projection shown in fig. 4(c).

A partial-wave analysis shows that the J^{PC} of this structure is 1^{--}. Its pole position is determined to be $(1576^{+49+98}_{-55-91})\,\mathrm{MeV}/c^2 - i(409^{+11+32}_{-12-67})\,\mathrm{MeV}/c^2$, and the branching ratio is $B(J/\psi \to X\pi^0) \cdot B(X \to K^+K^-) = (8.5 \pm 0.6^{+2.7}_{-3.6}) \times 10^{-4}$, where the first errors are statistical

and the second are systematic. These parameters are not compatible with any known meson resonances [12].

To understand the nature of the broad 1^{--} peak, it is important to search for a similar structure in $J/\psi \to K_S K^{\pm}\pi^{\mp}$ decays to determine its isospin. It is also intriguing to search for $K^*K, KK\pi$ decay modes. In the mass region of the X, there are several other 1^{--} states, such as the $\rho(1450)$ and $\rho(1700)$, but the width of the X is much broader than the widths of these other mesons. This may be an indication that the X has a different nature than these other mesons. For example, very broad widths are expected for multiquark states [32].

6 Summary

Based on 5.8×10^7 J/ψ events accumulated at the BES II detector, the X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$, the $\omega\phi$ threshold enhancement in $J/\psi \to \gamma\omega\phi$ and a broad 1^{--} resonant structure around $1.5\,\mathrm{GeV}/c^2$ in the K^+K^- mass spectrum in $J/\psi \to K^+K^-\pi^0$ are observed. And partial-wave analysis shows that $\eta(1760)$ is dominant in the $\omega\omega$ in the invariant-mass spectrum in $J/\psi \to \gamma\omega\omega$.

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