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

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The decay channel $J/\psi \to \gamma\pi^+\pi^-\eta'$ is analyzed using a sample of 5.8×10^7 J/ψ events collected with the BESII detector. A resonance, the $X(1835)$, is observed in the $\pi^+\pi^-\eta'$ invariant mass spectrum with a statistical significance of 7.7σ. A fit with a Breit-Wigner function yields a mass $M = 1833.7 \pm 6.1(stat) \pm 2.7(syst)$ MeV/c^2, a width $\Gamma = 67.7 \pm 20.3(stat) \pm 7.7(syst)$ MeV/c^2 and a product branching fraction $B(J/\psi \to \gamma X) \cdot B(X \to \pi^+\pi^-\eta') = (2.2 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-4}$. The mass and width of the $X(1835)$ are not compatible with any known meson resonance. Its properties are consistent with expectations for the state that produces the strong $p\bar{p}$ mass threshold enhancement observed in the $J/\psi \to \gamma p\bar{p}$ process at BESII.

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An anomalous enhancement near the mass threshold in the $p\overline{p}$ invariant mass spectrum from $J/\psi \to \gamma p\overline{p}$ decays was reported by the BES II experiment [1]. This enhancement was fitted with a sub-threshold S-wave Breit-Wigner resonance function with a mass $M = 1859^{+\ 3+\ 5}_{-10-25}$ MeV/c^2, a width $\Gamma < 30$ MeV/c^2 (at the 90% C.L.) and a product branching fraction (BF) $B(J/\psi \to \gamma X) \cdot B(X \to p\overline{p}) = (7.0 \pm 0.4(stat)^{+1.9}_{-0.8}(syst)) \times 10^{-5}$. This surprising experimental observation has stimulated a number of theoretical speculations [2, 3, 4, 5, 6, 7] and motivated the subsequent experimental observation of a strong $p\overline{\Lambda}$ mass threshold enhancement in $J/\psi \to pK^-\overline{\Lambda}$ decay [8]. Among various theoretical interpretations of the $p\overline{p}$ mass threshold enhancement, the most intriguing one is that of a $p\overline{p}$ bound state, sometimes called *baryonium* [2, 5, 9], which has been the subject of many experimental searches [10].

The baryonium interpretation of the $p\overline{p}$ mass enhancement requires a new resonance with a mass around 1.85 GeV/c^2 and it would be supported by the observation of the resonance in other decay channels. Possible decay modes for a $p\overline{p}$ bound state, suggested in Ref. [4, 5], include $\pi^+\pi^-\eta'$. In this letter, we report an analysis on the $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay channel, and the observation of a resonance in the $\pi^+\pi^-\eta'$ mass spectrum with a mass around 1835 MeV/c^2, where the η' meson is detected in two decay modes, $\eta' \to \pi^+\pi^-\eta(\eta \to \gamma\gamma)$ and $\eta' \to \gamma\rho$. In the following, this resonance is designated as the $X(1835)$. The results reported here are based on a sample of 5.8×10^7 J/ψ decays detected with the upgraded Beijing Spectrometer (BESII) at the Beijing Electron-Positron Collider (BEPC).

BESII is a large solid-angle magnetic spectrometer that is described in detail in Ref. [11]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 1.78\%\sqrt{1+p^2(\mathrm{GeV/c^2})}$ in a 40-layer cylindrical main drift chamber (MDC). Particle identification is accomplished by specific ionization (dE/dx) measurements in the MDC and time-of-flight (TOF) measurements in a barrel-like array of 48 scintillation counters. The dE/dx resolution is $\sigma_{dE/dx} = 8.0\%$; the TOF resolution is measured to be $\sigma_{TOF} = 180$ ps for Bhabha events. Outside of the time-of-flight counters is a 12-radiation-length barrel shower counter (BSC) comprised of gas tubes interleaved with lead sheets. The BSC measures the energies and directions of photons with resolutions of $\sigma_E/E \simeq 21\%/\sqrt{E(\mathrm{GeV})}$, $\sigma_\phi = 7.9$ mrad, and $\sigma_z = 2.3$ cm. The iron flux return of the magnet is instrumented with three double layers of counters that are used to identify muons. In this analysis, a GEANT3-based Monte Carlo (MC) package with detailed consideration of the detector performance is used. The consistency between data and MC has been carefully checked in many high-purity physics channels, and the agreement is reasonable [12].

For the $J/\psi \to \gamma\pi^+\pi^-\eta'(\eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma)$ channel, candidate events are required to have four charged tracks, each of which is well fitted to a helix that is within the polar angle region $|\cos\theta| < 0.8$ and with a transverse momentum larger than 70 MeV/c. The total charge of the four tracks is required to be zero. For each track, the TOF and dE/dx information are combined to form particle identification confidence levels for the π, K and p hypotheses; the particle type with the highest confidence level is assigned to each track. At least three of the charged tracks are required to be identified as pions. Candidate photons are required to have an energy deposit in the BSC greater than 60 MeV and to be isolated from charged tracks by more than 5°; the number of photons are required to be three. A four-constraint (4C) energy-momentum conservation kinematic fit is performed to the $\pi^+\pi^-\pi^+\pi^-\gamma\gamma\gamma$ hypothesis and the χ^2_{4C} is required to be less than 8 and also less than the χ^2 for the kinematically similar $K^+K^-\pi^+\pi^-\gamma\gamma\gamma$ hypothesis. An η signal is evident in the $\gamma\gamma$ invariant-mass distribution of all $\gamma\gamma$ pairings (Fig. 1(a)). In order to reduce combinatorial backgrounds from $\pi^0 \to \gamma\gamma$ decays, we require that the invariant masses of all $\gamma\gamma$ pairings are greater than 0.22 GeV/c^2. Candidate η mesons are selected by requiring $|M_{\gamma\gamma} - m_\eta| < 0.05$ GeV/c^2. The events are then subjected to a five-constraint (5C) fit where the invariant mass of the $\gamma\gamma$ pair associated with the η is constrained to m_η, and $\chi^2_{5C} < 15$ is required. The 5C-fit improves the $M_{\pi^+\pi^-\eta}$ mass resolution from 20 MeV/c^2 (for the 4C-fit) to 7 MeV/c^2. Figure 1(b) shows the $\pi^+\pi^-\eta$ invariant mass distribution after the 5C fit, where a clear η' signal is visible. For η' candidates, we select $\pi^+\pi^-\eta$ combinations with $|M_{\pi^+\pi^-\eta} - m_{\eta'}| < 0.015$ GeV/c^2. In a small fraction of events, more than one combination passes the above selection. In these cases the combination with $M_{\pi^+\pi^-\eta}$ closest to η' mass is used [13]. The $\pi^+\pi^-\eta'$ invariant mass spectrum for the selected events is shown in Fig. 1(c), where a peak at a mass around 1835 MeV/c^2 is observed.

For the $J/\psi \to \gamma\pi^+\pi^-\eta'(\eta' \to \gamma\rho)$ channel, events with four charged tracks (with zero net charge) and two photons are selected. At least three of the charged tracks

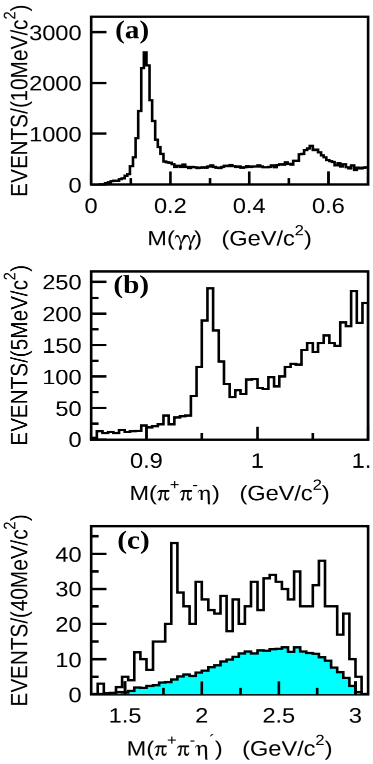

FIG. 1: Invariant mass distributions for selected $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'(\eta' \rightarrow \pi^+\pi^-\eta, \eta \rightarrow \gamma\gamma)$ candidate events. (a) The invariant mass distribution of $\gamma\gamma$ pairs. (b) The $\pi^+\pi^-\eta$ invariant mass distribution. (c) The $\pi^+\pi^-\eta'$ invariant mass distributions; the open histogram is data and the shaded histogram is $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ phase-space MC events (with arbitrary normalization).

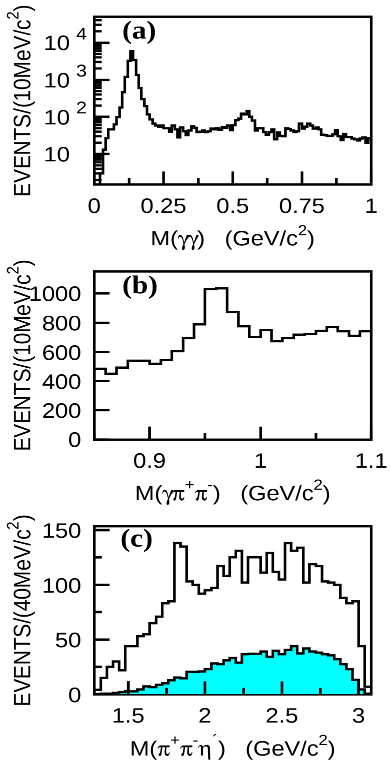

FIG. 2: Invariant mass distributions for the selected $J/\psi \rightarrow \pi^+\pi^-\eta'(\eta' \rightarrow \gamma\rho)$ candidate events, (a) The invariant mass distribution for $\gamma\gamma$ pairs. (b) The $\gamma\pi^+\pi^-$ invariant mass distribution. (c) The $\pi^+\pi^-\eta'$ invariant mass distributions: the open histogram is data and the shaded histogram is from $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ phase-space MC events (with arbitrary normalization).

are required to be identified as pions. These events are subjected to a 4C kinematic fit to the $\pi^+\pi^-\pi^+\pi^-\gamma\gamma$ hypothesis, and the χ^2_{4C} is required to be less than 8 and less than the χ^2 for the $K^+K^-\pi^+\pi^-\gamma\gamma$ hypothesis. At this stage of the analysis, the primary remaining background contributions are due to $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$, $J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\eta$, and $J/\psi \rightarrow \omega(\omega \rightarrow \gamma\pi^0)\pi^+\pi^-\pi^+\pi^-$; these produce peaks at m_{π^0}, m_η and m_ω in the $\gamma\gamma$ invariant mass distribution shown in Fig. 2(a). We suppress these backgrounds by rejecting events with $M_{\gamma\gamma} < 0.22$ GeV/c^2, $|M_{\gamma\gamma} - m_\eta|$ <0.05 GeV/c^2 or 0.72 GeV/c^2< $M_{\gamma\gamma} < 0.82$ GeV/c^2. To select ρ and η' signals, all $\pi^+\pi^-$ and $\gamma\pi^+\pi^-$ combinations are considered. The $\gamma\pi^+\pi^-$ invariant mass distribution shows an η' signal (Fig. 2(b)). We require that $|M_{\pi^+\pi^-} - m_\rho| < 0.2$ GeV/c^2 and $|M_{\gamma\pi^+\pi^-} - m_{\eta'}| < 0.025$ GeV/c^2. If more than one combination passes these criteria, the combination with $M_{\gamma\pi^+\pi^-}$ closest to $m_{\eta'}$ is selected [13]. For this channel there is also a distinct peak near 1835 MeV/c^2 in the $\pi^+\pi^-\eta'$ invariant mass spectrum (Fig. 2(c)).

To ensure that the peak near 1835 MeV/c^2 is not due to background, we have made extensive studies of potential background processes using both data and MC. Non-η' processes are studied with η' mass-sideband events. The main background channel, $J/\psi \rightarrow \pi^0\pi^+\pi^-\eta'$, and other background processes with multi-photons and/or with kaons are reconstructed with the data. In addition, we also checked for possible backgrounds with a MC sample of 60 million J/ψ decays generated by the LUND model [14]. None of these background sources produce a peak around 1835 MeV/c^2 in the $\pi^+\pi^-\eta'$ invariant mass spectrum.

Figure 3 shows the $\pi^+\pi^-\eta'$ invariant mass spectrum for the combined $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'(\eta' \rightarrow \pi^+\pi^-\eta)$ and $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'(\eta' \rightarrow \gamma\rho)$ samples (*i.e.*, the sum of the histograms in Figs. 1(c) and 2(c)). This spectrum is fitted with a Breit-Wigner (BW) function convolved with a Gaussian mass resolution function (with $\sigma = 13$ 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. 3) are $M = 1833.7 \pm 6.1$ MeV/c^2 and $\Gamma = 67.7 \pm 20.3$ MeV/c^2. The signal yield from the fit is 264 ± 54 events with a confidence level 45.5% ($\chi^2/d.o.f. = 57.6/57$) and $-2\ln L = 58.4$. A fit to the mass spectrum without a BW signal function returns $-2\ln L = 126.5$. The change in $-2\ln L$ with $\Delta(d.o.f.) = 3$ 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

$$B(J/\psi \to \gamma X(1835)) \cdot B(X(1835) \to \pi^+\pi^-\eta') = (2.2 \pm 0.4) \times 10^{-4}.$$

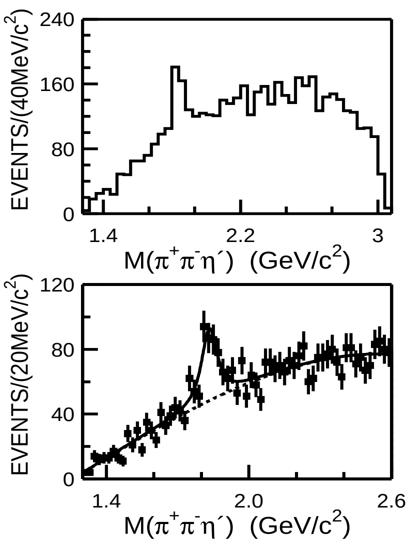

FIG. 3: The $\pi^+\pi^-\eta'$ invariant mass distribution for selected events from both the $J/\psi \to \gamma\pi^+\pi^-\eta'(\eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma)$ and $J/\psi \to \gamma\pi^+\pi^-\eta'(\eta' \to \gamma\rho)$ analyses. The bottom panel shows the fit (solid curve) to the data (points with error bars); the dashed curve indicates the background function.

The consistency between the two η' decay modes is checked by fitting the distributions in Fig. 1(c) and Fig. 2(c) separately with the method described above. The fit to Fig. 1(c) gives $M = 1827.4 \pm 8.1$ MeV/c^2 and $\Gamma = 54.2 \pm 34.5$ MeV/c^2 with a statistical significance of 5.1σ. From the 68$\pm$26 signal events obtained from the fit, the product BF is $B(J/\psi \to \gamma X(1835)) \cdot B(X(1835) \to \pi^+\pi^-\eta') = (1.8\pm0.7)\times10^{-4}$. Similar results are obtained if we only apply 4C kinematic fit in this analysis. For the fit to Fig. 2(c), the mass and width are determined to be $M = 1836.3 \pm 7.9$ MeV/c^2 and $\Gamma = 70.3 \pm 23.1$ MeV/c^2 with a statistical significance of 6.0 σ. For this mode alone, the signal yield of 193$\pm$43 signal events correspond to $B(J/\psi \to \gamma X(1835)) \cdot B(X(1835) \to \pi^+\pi^-\eta') = (2.3 \pm 0.5) \times 10^{-4}$. The $X(1835)$ mass, width and product BF values determined from the two η' decay modes separately are in good agreement with each other.

The systematic uncertainties on the mass and width are determined by varying the functional form used to represent the background, the fitting range of the mass spectrum, the mass calibration, and possible biases due to the fitting procedure. The latter are estimated from differences between the input and output mass and width values from MC studies. The total systematic errors on the mass and width are 2.7 MeV/c^2 and 7.7 MeV/c^2, respectively. The systematic error on the branching fraction measurement mainly comes from the uncertainties of MDC simulation (including systematic uncertainties of the tracking efficiency and the kinematic fits), the photon detection efficiency, the particle identification efficiency, the η' decay branching fractions to $\pi^+\pi^-\eta$ and $\gamma\rho$, the background function parameterization, the fitting range of the mass spectrum, the requirements on numbers of photons, the invariant mass distributions of $\gamma\gamma$ pairs in the two analyses, the $\pi^+\pi^-$ invariant mass distribution in $\eta' \to \gamma\pi^+\pi^-$ decays, MC statistics, the total number of J/ψ events [15], and the unknown spin-parity of the $X(1835)$. For the latter we use the difference between phase-space and a $J^{PC} = 0^{-+}$ hypothesis for the $X(1835)$. The total relative systematic error on the product branching fraction is 20.2%.

In summary, the decay channel $J/\psi \to \gamma\pi^+\pi^-\eta'$ is analyzed using two η' decay modes, $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \gamma\rho$. A resonance, the $X(1835)$, is observed with a high statistical significance of 7.7σ in the $\pi^+\pi^-\eta'$ invariant mass spectrum. From a fit with a Breit-Wigner function, the mass is determined to be $M = 1833.7 \pm 6.1(stat) \pm 2.7(syst)$ MeV/c^2, the width is $\Gamma = 67.7 \pm 20.3(stat) \pm 7.7(syst)$ MeV/c^2, and the product branching fraction is $B(J/\psi \to \gamma X) \cdot B(X \to \pi^+\pi^-\eta') = (2.2 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-4}$. The mass and width of the $X(1835)$ are not compatible with any known meson resonance [16]. In Ref. [16], the candidate closest in mass to the $X(1835)$ is the (unconfirmed) 2^{-+} $\eta_2(1870)$ with $M = 1842\pm8$ MeV/c^2. This state's width, $\Gamma = 225 \pm 14$ MeV/c^2, is considerably larger than that of the $X(1835)$ (see also [17], where the 2^{-+} component in the $\eta\pi\pi$ mode of J/ψ radiative decay has a mass 1840 ± 15 MeV/c^2 and a width 170 ± 40 MeV/c^2).

We examined the possibility that the $X(1835)$ is responsible for the $p\bar{p}$ mass threshold enhancement observed in radiative $J/\psi \to \gamma p\bar{p}$ decays [1]. It has been pointed out that the S-wave BW function used for the fit in Ref. [1] should be modified to include the effect of final-state-interactions (FSI) on the shape of the $p\bar{p}$ mass spectrum [6, 7]. Redoing the S-wave BW fit to the $p\bar{p}$ invariant mass spectrum of Ref. [1] including the zero Isospin, S-wave FSI factor of Ref. [7], yields a mass $M = 1831 \pm 7$ MeV/c^2 and a width $\Gamma < 153$ MeV/c^2 (at the 90% C.L.) [18]; these values are in good agreement with the mass and width of $X(1835)$ reported here. Moreover, according to Ref. [5], the $\pi\pi\eta'$ decay 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: $B(X \to p\bar{p})/B(X \to \pi^+\pi^-\eta') \sim 1/3$ [19]. 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 $p\overline{p}$ branching fraction implies an unusually strong coupling to $p\overline{p}$, as expected for a $p\overline{p}$ bound state [20]. However, other possible interpretations of the $X(1835)$ that have no relation to the $p\overline{p}$ mass threshold enhancement are not excluded.

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