| Title | Confirmation of the X(1835) and observation of the resonances X(2120) and X(2370) in J/ψ → γπ⁺π⁻ + η′ |
Confirmation of the \(X(1835)\) and Observation of the Resonances \(X(2120)\) and \(X(2370)\) in \(J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'\)

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\(X(1835)\) and \(X(2120)\) and \(X(2370)\) in \(J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'\)

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confirm the existence of the sample collected with BESIII provides an opportunity to study a pseudoscalar, which was previously observed by BESIII, is confirmed with a statistical significance that is larger than 20σ. In addition, some interpretations of the X(1835) may be a good channel for finding this pseudoscalar glueball. One of the strongest decay channels of the ηc is π+π−η′. Thus J/ψ → γπ+π−η′ may be a good channel for finding 0− glueballs.

In this Letter, we report a study of J/ψ → γπ+π−η′ that uses two η′ decay modes, η′ → γρ and η′ → π+π−η′. The analysis uses a sample of (225.2 ± 2.8) × 10^6 J/ψ events [13] accumulated in the new BESIII Detector (BESIII) [14] located at the Beijing Electron-Positron Collider (BECII) [15] at the Beijing Institute of High Energy Physics.

BEPCII is a two-ring e+e− collider designed for a peak luminosity of 10^{35} cm^{-2} s^{-1} at a beam current of 0.93 A. The cylindrical core of the BESIII detector consists of a helium-gas-based drift chamber, a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter.
calorimeter, all enclosed in a superconducting solenoidal magnet providing a 1.0-T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The charged particle and photon acceptance is 93% of 4π, and the charged particle momentum and photon energy resolutions at 1 GeV are 0.5% and 2.5%, respectively. The time resolution of TOF is 80 ps in the barrel and 110 ps in the endcaps, and the dE/dx resolution is 6%.

Charged-particle tracks in the polar angle range |cosθ| < 0.93 are reconstructed from hits in the helium-gas-based drift chamber. Tracks that extrapolate to be within 20 cm of the interaction point in the beam direction and 2 cm in the plane perpendicular to the beam are selected. The TOF and dE/dx information are combined to form particle identification confidence levels for the π, K, and p hypotheses; each track is assigned to the particle type that corresponds to the hypothesis with the highest confidence level. Photon candidates are required to have at least 100 MeV of energy in the electromagnetic calorimeter regions |cosθ| < 0.8 and 0.86 < |cosθ| < 0.92 and be isolated from all charged tracks by more than 5°. In this analysis, candidate events are required to have four charged tracks (zero net charge) with at least three of the charged tracks identified as pions. At least two photons (three photons) are required for the η′ → γγ (η′ → π+ π− η) channel.

For J/ψ → γπ+ π− η′ (η′ → γγ), a four-constraint (4C) energy-momentum conservation kinematic fit is performed to the γπ+ π− π+ π− hypothesis. For events with more than two photon candidates, the combination with the minimum χ2 is used, and χ2<sub>4C</sub> < 40 is required. Events with |M<sub>γγ</sub> − m<sub>ππ</sub>| < 0.04 GeV/c², |M<sub>γγ</sub> − m<sub>η</sub>| < 0.03 GeV/c², 0.72 GeV/c² < M<sub>γγ</sub> < 0.82 GeV/c², or |M<sub>ππππ</sub> − m<sub>η</sub>| < 0.007 GeV/c² are rejected to suppress the background from π<sup>0</sup>π<sup>0</sup> → π+ π− π+ π−, ηπ+ π− π+ π−, ω(ω → γγ0)π+ π− π+ π−, and γπ+ π− η(η → γπ+ π−), respectively. A clear η′ signal with a 5 MeV/c² mass resolution is evident in the mass spectrum of all selected γπ+ π− combinations shown in Fig. 1(a). Candidate ρ and η′ mesons are reconstructed from the π+ π− and γπ+ π− pairs with |M<sub>ππ</sub> − m<sub>ρ</sub>| < 0.2 GeV/c² and |M<sub>ππππ</sub> − m<sub>η′</sub>| < 0.015 GeV/c², respectively. If more than one combination passes these criteria, the combination with M<sub>ππππ</sub> closest to m<sub>η′</sub> is selected. After the above selection, the X(1835) resonance is clearly visible in the π+ π− η′ invariant-mass spectrum of Fig. 1(b). Also, additional peaks are evident around 2.1 and 2.4 GeV/c² as well as a distinct signal for the η′.

For J/ψ → γπ+ π− η′ (η′ → π+ π− η), a 4C kinematic fit to the γγγπ+ π− π+ π− hypothesis is performed. If there are more than three photon candidates, the combination with the minimum χ2<sub>4C</sub> is selected, and χ2<sub>4C</sub> < 40 is required. In order to reduce the combinatorial background events from π<sup>0</sup> → γγ, |M<sub>γγ</sub> − m<sub>ππ</sub>| > 0.04 GeV/c² is required for all photon pairs. The η candidates are selected by requiring |M<sub>γγ</sub> − m<sub>η</sub>| < 0.03 GeV/c². A five-constraint fit with an η mass constraint is used to improve the mass resolution from 8 MeV/c² (4C) to 3 MeV/c², as shown in Fig. 1(c) where χ2<sub>5C</sub> < 40 is required. To select η′ mesons, |M<sub>ππππ</sub> − m<sub>η′</sub>| < 0.01 GeV/c² is required. If more than one combination passes the above selection, the combination with M<sub>ππππ</sub> closest to m<sub>η′</sub> is selected. After the above selection, structures similar to those seen for the η′ → γρ channel in the π+ π− η′ invariant-mass spectrum can be seen in Fig. 1(d), namely, peaks near 1.8, 2.1, and 2.4 GeV/c² as well as the η′.

Potential background processes are studied with an inclusive sample of 2 × 10<sup>8</sup> J/ψ events generated according to the Lund-Charm model [16] and the Particle Data Group (PDG) decay tables [17]. There are no peaking backgrounds at the positions of the three resonances. To ensure further that the three peaks are not due to background, we have studied potential exclusive background processes using data. The main background channel is from J/ψ → π<sup>0</sup>π<sup>0</sup>π− η′. Non-η′ processes are studied with η′ mass-sideband events. Neither of these produce peaking structures.

The π+ π− η′ invariant-mass spectrum for the combined two η′ decay modes is presented in Fig. 2. Here a small peak at the position of the f<sub>1</sub>(1510) signal is also present. Fits to the mass spectra have been made using four
efficiency-corrected Breit-Wigner functions convolved with a Gaussian mass resolution plus a nonresonant \( \pi^+ \pi^- \eta' \) contribution and background representations, where the efficiency for the combined channels is obtained from the branching-ratio-weighted average of the efficiencies for the two \( \eta' \) modes. The contribution from nonresonant \( \gamma \pi^+ \pi^- \eta' \) production is described by reconstructed Monte Carlo (MC)-generated \( J/\psi \rightarrow \gamma \pi^+ \pi^- \eta' \) phase space decays, and it is treated as an incoherent process. The background contribution can be divided into two different components: the contribution from non-\( \eta' \) events estimated from \( \eta' \) mass sideband, and the contribution from \( J/\psi \rightarrow \pi^0 \pi^+ \pi^- \eta' \). For the second background, we obtain the background \( \pi^+ \pi^- \eta' \) mass spectrum from data by selecting \( J/\psi \rightarrow \pi^0 \pi^+ \pi^- \eta' \) events and reweighting their mass spectrum with a weight equal to the MC efficiency ratio of the \( \gamma \pi^+ \pi^- \eta' \) and \( \pi^0 \pi^+ \pi^- \eta' \) selections for \( J/\psi \rightarrow \pi^0 \pi^+ \pi^- \eta' \). The masses, widths, and number of events of the \( f_1(1510) \), the \( X(1835) \) and the resonances near 2.1 and 2.4 GeV/c^2, the \( X(2120) \) and \( X(2370) \), are listed in Table I. The statistical significance is determined from the change in \(-2\ln L \) in the fits to mass spectra with and without signal assumption while considering the change of degree of freedom of the fits. With the systematic uncertainties in the fit taken into account, the statistical uncertainty in the fit taken into account, the statistical significance of the \( X(1835) \) is larger than 20\( \sigma \), while those for the \( f_1(1510) \), the \( X(2120) \), and the \( X(2370) \) are larger than 5.7\( \sigma \), 7.2\( \sigma \), and 6.4\( \sigma \), respectively. The mass and width from the fit of the \( f_1(1510) \) are consistent with PDG values [17]. With MC-determined selection efficiencies of 16.0\% and 11.3\% for the \( \eta' \rightarrow \eta \rho \) and \( \eta' \rightarrow \pi^+ \pi^- \eta \) decay modes, respectively, the branching fraction for the \( X(1835) \) is measured to be \( B(J/\psi \rightarrow \gamma X(1835)) \) \( B(X(1835) \rightarrow \pi^+ \pi^- \eta') = (2.87 \pm 0.09) \times 10^{-4} \). The consistency between the two \( \eta' \) decay modes is checked by fitting their \( \pi^+ \pi^- \eta' \) mass distribution separately with the procedure described above.

For radiative \( J/\psi \) decays to a pseudoscalar meson, the polar angle of the photon in the \( J/\psi \) center of mass system, \( \theta_\gamma \), should be distributed according to \( 1 + \cos^2 \theta_\gamma \). We divide the \( |\cos \theta_\gamma| \) distribution into 10 bins in the region of \([0, 1, 0]\). With the same procedure as described above, the number of the \( X(1835) \) events in each bin can be obtained by fitting the mass spectrum in this bin, and then the background-subtracted, acceptance-corrected \( |\cos \theta_\gamma| \) distribution for the \( X(1835) \) is obtained as shown in Fig. 3, where the errors are statistical only. It agrees with \( 1 + \cos^2 \theta_\gamma \), which is expected for a pseudoscalar, with \( \chi^2/\text{d.o.f} = 11.8/9 \).

The systematic uncertainties on the mass and width are mainly from the uncertainty of background representation, the mass range included in the fit, different shapes for background contributions, and the nonresonant process and contributions of possible additional resonances in the 1.6 GeV/c^2 and 2.6 GeV/c^2 mass regions. The total systematic errors on the mass and width are \( +5.6 \) and \( -2.1 \) and

### Table I. Fit results with four resonances for the combined two \( \eta' \) decay modes

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( M(\text{MeV}/c^2) )</th>
<th>( \Gamma(\text{MeV}/c^2) )</th>
<th>( N_{\text{event}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1(1510) )</td>
<td>1522.7 \pm 5.0</td>
<td>48 \pm 11</td>
<td>230 \pm 37</td>
</tr>
<tr>
<td>( X(1835) )</td>
<td>1836.5 \pm 3.0</td>
<td>190.1 \pm 9.0</td>
<td>4265 \pm 131</td>
</tr>
<tr>
<td>( X(2120) )</td>
<td>2122.4 \pm 6.7</td>
<td>83 \pm 16</td>
<td>647 \pm 103</td>
</tr>
<tr>
<td>( X(2370) )</td>
<td>2376.3 \pm 8.7</td>
<td>83 \pm 17</td>
<td>565 \pm 105</td>
</tr>
</tbody>
</table>

![Fig. 2](image-url) (color online). (a) The \( \pi^+ \pi^- \eta' \) invariant-mass distribution for the selected events from the two \( \eta' \) decay modes. (b) Mass spectrum fitting with four resonances; here, the dash-dotted line is contributions of non-\( \eta' \) events and the \( \pi^0 \pi^+ \pi^- \eta' \) background for two \( \eta' \) decay modes, and the dashed line is contributions of the total background and nonresonant \( \pi^+ \pi^- \eta' \) process.

![Fig. 3](image-url) The background-subtracted, acceptance-corrected \( |\cos \theta_\gamma| \) distribution of the \( X(1835) \) for two \( \eta' \) decay modes for \( J/\psi \rightarrow \gamma \pi^+ \pi^- \eta' \).
are measured to be $2$ dips around the BESII result, but the width is significantly larger. If we fit the $10^9$ ground estimation, and the total relative systematic error of the interference cannot be done. In the absence of knowledge of the spin parities of the resonances and their decay intermediate states, reliable fits that include interference cannot be done. In summary, the decay channel $J/\psi \rightarrow \pi^+\pi^-\eta'$ is analyzed using two $\eta'$ decay modes, $\eta' \rightarrow \gamma\rho$ and $\eta' \rightarrow \pi^+\pi^-\eta$. The $X(1835)$, which was first observed at BESII, has been confirmed with a statistical significance larger than 20$\sigma$. Meanwhile, two resonances, the $X(2120)$ and the $X(2370)$ are observed with statistical significances larger than 7.2$\sigma$ and 6.4$\sigma$, respectively. The masses and widths are measured to be

$X(1835)$

$$M = 1836.5 \pm 3.0 \text{(stat)} \pm 5.6 \text{(syst)} \text{MeV}/c^2$$

$$\Gamma = 190 \pm 9 \text{(stat)} \pm 38 \text{(syst)} \text{MeV}/c^2$$

$X(2120)$

$$M = 2122.4 \pm 6.7 \text{(stat)} \pm 4.7 \text{(syst)} \text{MeV}/c^2$$

$$\Gamma = 83 \pm 16 \text{(stat)} \pm 31 \text{(syst)} \text{MeV}/c^2$$

$X(2370)$

$$M = 2376.3 \pm 8.7 \text{(stat)} \pm 3.3 \text{(syst)} \text{MeV}/c^2$$

$$\Gamma = 83 \pm 17 \text{(stat)} \pm 44 \text{(syst)} \text{MeV}/c^2$$

For the $X(1835)$, the product branching fraction is $B[J/\psi \rightarrow \gamma X(1835)] \cdot B(X(1835) \rightarrow \pi^+\pi^-\eta') = [2.87 \pm 0.09 \text{(stat)} \pm 0.52 \text{(syst)}] \times 10^{-4}$, and the angular distribution of the radiative photon is consistent with a pseudoscalar assignment. The mass of the $X(1835)$ is consistent with the BESII result, but the width is significantly larger. If we fit the mass spectrum with one resonance as BESII, the mass and width of the $X(1835)$ are 1841.2 $\pm$ 2.9 MeV/c$^2$ and 109 $\pm$ 11 MeV/c$^2$, where the errors are statistical only.

In the mass spectrum fitting in Fig. 2(b), possible interferences among different resonances and the nonresonant process are not taken into account which might be a source of the large $\chi^2$ value for the fit ($\chi^2$/d.o.f = 144/62). The dips around 2.2 GeV/c$^2$ and 2.5 GeV/c$^2$ may not be fitted well due to the neglect of such interferences. In the absence of knowledge of the spin parities of the resonances and their decay intermediate states, reliable fits that include interference cannot be done. It is intriguing that it is the first time resonant structures are observed in the 2.3 GeV/c$^2$ region in the $\pi^+\pi^-\eta'$ mode and in $J/\psi$ radiative decays which a $0^+$ glueball may favor to decay to and to be produced from. To understand the nature of the $X(1835)$, $X(2120)$, and $X(2370)$, it would be crucial to measure their spin parities and to search for them in more decay modes and in more production mechanisms. To determine their spin parities, and to measure their masses and widths more precisely, a partial wave analysis must be performed, which will be possible with the much higher statistics $J/\psi$ data samples planned for future runs of the BESIII experiment.

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