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Observation of a structure at 1.84 GeV/c^2 in the $3(\pi^+\pi^-)$ mass spectrum in $J/\psi \to \gamma 3(\pi^+\pi^-)$ decays

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With a sample of 225.3 million J/ψ events taken with the BESIII detector, the decay $J/\psi \to \gamma 3(\pi^+\pi^-)$ is analyzed. A structure at 1.84 GeV/c^2 is observed in the $3(\pi^+\pi^-)$ invariant mass spectrum with a statistical significance of 7.6σ . The mass and width are measured to be $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 and $\Gamma = 83 \pm 14 \pm 11$ MeV. The product branching fraction is determined to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$. No η' signals are observed in the $3(\pi^+\pi^-)$ invariant mass spectrum, and the upper limit of the branching fraction for the decay $\eta' \to 3(\pi^+\pi^-)$ is set to be 3.1×10^{-5} at a 90% confidence level.

Within the framework of Quantum Chromodynamics (QCD), the existence of gluon self-coupling suggests that in addition to conventional meson and baryon states, there may exist bound states such as glueballs, hybrid states and multiquark states. Experimental searches for glueballs and hybrid states have been carried out for many years, and so far no conclusive evidence has been found. The establishment of new forms of hadronic matter beyond simple quark-antiquark system remains one of the main interests in experimental particle physics.

Decays of the J/ψ particle have always been regarded as an ideal environment in which to study light hadron spectroscopy and search for new hadrons. At BESII, important advances in light hadron spectroscopy were made using studies of J/ψ radiative decays [1–3]. Of interest is the observation of the $X(1835)$ state in $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay, which was confirmed recently by BESIII [4] and CLEO-c [5]. Since the discovery of the $X(1835)$, many possible interpretations have been proposed, such as a $p\bar{p}$ bound state [6–9], a glueball [10, 11], or a radial excitation of the η' meson [12, 13]. In the search for the $X(1835)$ in other J/ψ hadronic decays, BESIII reported the first observation of the $X(1870)$ in $J/\psi \to \omega\pi^+\pi^-\eta$ [14]. More recently, BESIII performed spin-parity analyses of threshold structures, the $X(p\bar{p})$, observed in $J/\psi \to \gamma p\bar{p}$ [15], and the $X(1810)$, observed in $J/\psi \to \gamma\omega\phi$ [16]. The spin-parity of the $X(p\bar{p})$ is found to be 0^{-+} and the $X(1810)$ is confirmed to be a 0^{++} state. To understand their nature, further study is strongly needed, in particular, in searching for new decay modes.

Since the $X(1835)$ was confirmed to be a pseudoscalar particle [4] and it may have properties in common with the η_c. Six charged pions is a known decay mode of the η_c; therefore, J/ψ radiative decays to $3(\pi^+\pi^-)$ may be a favorable channel to search for the X states in the 1.8 - 1.9 GeV/c^2 region.

In this letter, we present results of a study of $J/\psi \to \gamma 3(\pi^+\pi^-)$ decays using a sample of $(225.3 \pm 2.8) \times 10^6$ J/ψ events [18] collected with the BESIII detector [19]. A structure at 1.84 GeV/c^2 (denoted as $X(1840)$ in this letter), is clearly observed in the mass spectrum of six charged pions. Meanwhile in an attempt to search for η' decaying into six charged pions, no η' signals are observed. The upper limit on the decay branching fraction is set at a 90% confidence level.

The BESIII detector is a magnetic spectrometer located at BEPCII [20], a double-ring e^+e^- collider with the design peak luminosity of 10^{33} cm^{-2}s^{-1} at a center of mass energy of 3.773 GeV. The cylindrical core of the BESIII detector consists of a helium-based main drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are 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 acceptance of charged particles and photons is 93% over 4π solid angle, and the charged-particle momentum resolution at 1 GeV/c is 0.5%. The EMC measures photon energies with the resolution of 2.5% (5%) at 1 GeV in the barrel (endcaps).

Monte Carlo (MC) simulations are used to estimate the backgrounds and determine the detection efficiency. Simulated events are processed using GEANT4 [21, 22], where measured detector resolutions are incorporated.

Charged tracks are reconstructed using hits in the MDC and are required to pass within ±10 cm from the interaction point in the beam direction and ±1 cm in the perpendicular plane to the beam. The polar angle of the charged tracks should be in the region $|\cos\theta| < 0.93$. Photon candidates are selected from showers in the EMC with the energy deposit in the EMC barrel region ($|\cos\theta| < 0.8$) greater than 25 MeV and in the EMC endcap region ($0.86 < |\cos\theta| < 0.92$) greater than 50 MeV. The photon candidates should be isolated from the charged tracks by an opening angle of 10°.

Candidate events are required to have six charged tracks with zero net charge and at least one photon. All the charged tracks are assumed to be pions. The candidate events are required to successfully pass a primary vertex fit. A four-momentum constraint (4C) kinematic fit is performed to the $J/\psi \to \gamma 3(\pi^+\pi^-)$ hypothesis, and the χ^2_{4C} is required to be less than 30. If the number of photon candidates is more than one, the $\gamma 3(\pi^+\pi^-)$ combination with the minimum χ^2_{4C} is selected. To suppress background events with multi-photons in the final states, $P^2_{t\gamma} = 2|\vec{P}_{\rm miss}|^2(1-\cos\theta_{\rm miss})$ is required to be less than 0.0004 GeV^2/c^2, where $\vec{P}_{\rm miss}$ is the missing momentum of the six charged tracks and $\theta_{\rm miss}$ is the angle between the missing momentum and the momentum of the radiative photon. To further reject backgrounds with additional photons in the final state, the χ^2_{4C} of four-constraint kinematic fit in the hypothesis of $J/\psi \to \gamma 3(\pi^+\pi^-)$ is required to be less than that of the $\gamma\gamma 3(\pi^+\pi^-)$ hypothesis, and the $\gamma\gamma$ invariant mass in the $\gamma\gamma 3(\pi^+\pi^-)$ hypothesis is required to be $|M(\gamma\gamma) - M(\pi^0)| > 0.01$ GeV/c^2. To suppress background events with $K_S \to \pi^+\pi^-$ in the final state, K_S candidates are reconstructed from secondary vertex fits to all oppositely charged track pairs. The invariant mass $M(\pi^+\pi^-)$ must be within the range $|M(\pi^+\pi^-) - M(K_S)| < 0.005$ GeV/c^2, where the $M(K_S)$ is the nominal K_S mass [17]. The number of K_S candidates is required to be less than 2.

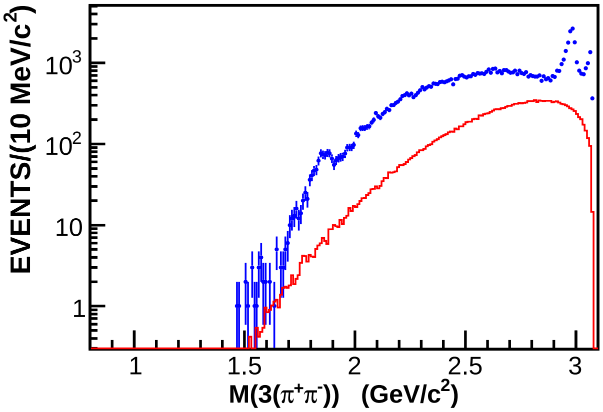

FIG. 1. Distribution of the invariant mass of $3(\pi^+\pi^-)$ from $J/\psi \to \gamma 3(\pi^+\pi^-)$ events. The dots with error bars are data; the histogram is phase space events with an arbitrary normalization.

Figure 1 shows the $3(\pi^+\pi^-)$ invariant mass spectrum for events that survive the above selection criteria, where a clear η_c peak is observed around 2.98 GeV/c^2, no evident η' signal is observed, and a distinct enhancement is seen around 1.84 GeV/c^2. In Fig. 2, the $M(3(\pi^+\pi^-))$ distribution is plotted in the range [1.55, 2.15] GeV/c^2.

To investigate possible backgrounds, we use a MC sample of 225 million simulated J/ψ decays, in which the decays with known branching fractions [17] are generated by BesEvtGen [23] and unmeasured J/ψ decays by the Lundcharm model [24]. With the same selection criteria, we find no evident structure at 1.84 GeV/c^2. The background resulting from other, incorrectly reconstructed event topologies is mainly from $J/\psi \to \pi^0 3(\pi^+\pi^-)$, which show no structure at 1.84 GeV/c^2 in the $3(\pi^+\pi^-)$ mass spectrum. To estimate this contribution, we reconstruct the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ decay from data and

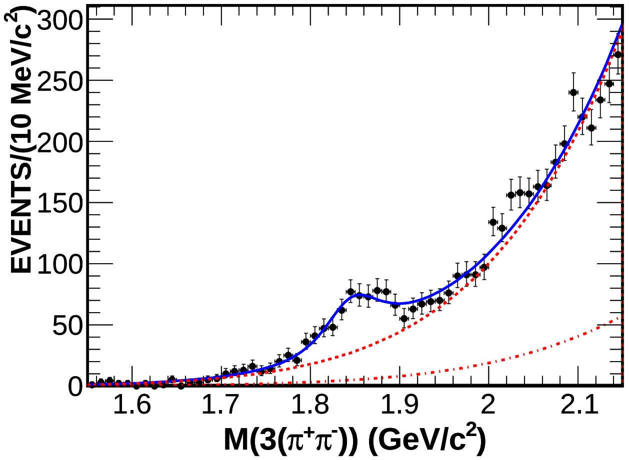

FIG. 2. The fit of mass spectrum of $3(\pi^+\pi^-)$. The dots with error bars are data; the solid line is the fit result. The dashed line represents all the backgrounds, including the background events from $J/\psi \to \pi^0 3(\pi^+\pi^-)$ (dash-dotted line, fixed in the fit) and a third-order polynomial representing other backgrounds.

then re-weight the $3(\pi^+\pi^-)$ invariant mass spectrum by a multiplicative weighting factor $\varepsilon_1/\varepsilon_2$, where ε_1 and ε_2 are the efficiencies for $J/\psi \to \pi^0 3(\pi^+\pi^-)$ MC events to pass $J/\psi \to \gamma 3(\pi^+\pi^-)$ and $J/\psi \to \pi^0 3(\pi^+\pi^-)$ selection criteria, respectively. The selection criteria for $J/\psi \to \pi^0 3(\pi^+\pi^-)$ are similar to those applied to $J/\psi \to \gamma 3(\pi^+\pi^-)$ except for the requirement of an additional photon. The background analysis shows that the structure at 1.84 GeV/c^2 in the $3(\pi^+\pi^-)$ mass spectrum does not come from background events.

To extract the number of signal events associated with the peaking structure, an unbinned maximum likelihood fit is applied to the six pion mass spectrum. The fit includes three components: a signal shape, shapes for the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ background and other backgrounds, which have the same final states, but not contribute to the structure around 1.84 GeV/c^2. The signal shape is described with a Breit-Wigner function modified by the effects of the phase space factor and the detection efficiency, which is determined by a phase-space MC simulation of $J/\psi \to \gamma 3(\pi^+\pi^-)$. The Breit-Wigner function is convolved with a Gaussian function to account for the detector resolution (5.1 MeV/c^2, determined from MC simulation). For the background shape, the contribution from the $J/\psi \to \pi^0 3(\pi^+\pi^-)$ background, which is fixed in the fit and shown by the dash-dotted line in Fig. 2, is represented by the re-weighted $3(\pi^+\pi^-)$ invariant mass spectrum, while other contributions are represented by a third-order polynomial. The total background is shown as the dashed line in Fig. 2.

The fit yields 632±93 events in the peak at 1842.2±4.2 MeV/c^2 and a width of Γ=83±14 MeV. The statistical significance of the signal is determined from the change in log likelihood and the change of number of degrees of freedom (d.o.f) in the fit with and without the structure $X(1840)$. Different possibilities have been studied by varying the fit range and the background shapes and by removing the phase space factor. Among all possibilities the smallest statistical significance was 7.6σ corresponding to -2ΔlnL=67 and Δd.o.f=3. With the detection efficiency, (11.5±0.1)%, obtained from the phase space MC simulation, the product branching fraction is measured to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36) \times 10^{-5}$, where the error is statistical only.

No η' events are observed in the $3(\pi^+\pi^-)$ mass spectrum. The upper limit at the 90% confidence level is 2.44 events with the confidence intervals suggested in Ref. [25]. The detection efficiency in the mass region [0.928, 0.988] GeV/c^2 is determined to be (7.8 ± 0.1)% from the MC simulation. Since only the statistical error is considered when we obtain the 90% upper limit of the number of events, the upper limit of the number of events is shifted up by one sigma of the total systematic uncertainty shown below in Table I. With the number of J/ψ events and the measured $B(J/\psi \to \gamma\eta') = (5.16 \pm 0.15) \times 10^{-3}$ [17], the upper limit of the branching fraction is obtained to be $B(\eta' \to 3(\pi^+\pi^-)) < 3.1 \times 10^{-5}$.

Sources of systematic errors and their corresponding contributions to the measurement of the branching fractions are summarized in Table I. The uncertainties in tracking and photon detection have been studied [26] and the difference between data and MC is about 2% per charged track and 1% per photon, which is taken as the systematic error. Uncertainty associated with the 4C kinematic fit comes from the inconsistency between data and MC simulation of the fit; this difference is reduced by correcting the track helix parameters of MC simulation, as described in detail in Ref. [27]. In this analysis, we take the efficiency with correction as the nominal value, and take the difference between the efficiencies with and without correction as the systematic uncertainty from the kinematic fit. The background uncertainty is determined by changing the background functions and the fit range. The uncertainties from the mass spectrum fit include contributions from the variation of the phase space factor and the possible impact of other resonances (eg. $f_2(2010)$). The systematic error for the $P^2_{t\gamma}$ selection criterion is estimated with the sample of $J/\psi \to \pi^0 3(\pi^+\pi^-)$ by comparing the efficiency of this requirement between MC and data. For the detection efficiency uncertainty due to the unknown spin-parity of the structure, we use the difference between phase space and a pseudoscalar meson hypothesis. The uncertainties from MC statistics, the branching fraction of $J/\psi \to \gamma\eta'$ [17] and the flux of J/ψ events [18] are also considered. We assume all of these sources are independent, and take the total systematic error to be their sum in quadrature.

The systematic uncertainties on mass and width are estimated from the mass scale, background shape, fitting range, mass spectrum fit, and possible biases due to the fitting procedure. The uncertainty from the detector resolution is checked by using a double Gaussian function as the resolution function, and the change is found to be negligible. The uncertainty from the mass scale is estimated by fitting the η_c resonance in $M(3(\pi^+\pi^-))$ spectrum. Uncertainties from the background shape and fitting range are estimated by varying the functional form used to represent the background and the fitting range. Uncertainties from mass spectrum fit include contributions from the variation of the phase space factor and the possible impact of other resonances (eg. $f_2(2010)$). Possible biases due to the fitting procedure are estimated from differences between the input and output of the mass and width values from MC studies. Adding these sources in quadrature, the total systematic error on the mass is $^{+7.1}_{-2.6}$ MeV/c^2 and on the width is ±11 MeV.

TABLE I. Summary of the systematic uncertainties in the branching fractions (in unit of %).

Sources	$X(1840)$	η'
MDC tracking	12	12
Photon detection	1	1
$P^2_{t\gamma}$ cut	2.0	2.0
Kinematic fit	4.3	5.1
Background uncertainty	17.1	-
Mass spectrum fit	$^{+10.3}_{-20.3}$	-
Detection efficiency	6.1	-
MC statistics	0.9	1.3
$B(J/\psi \to \gamma\eta')$	-	2.9
Number of J/ψ events	1.2	1.2
Total	$^{+24.6}_{-30.2}$	13.7

In summary, we studied the decay $J/\psi \to \gamma 3(\pi^+\pi^-)$ with a 225.3 million J/ψ event sample [18] accumulated at the BESIII detector. A structure at 1.84 GeV/c^2 is observed in the $3(\pi^+\pi^-)$ mass spectrum with a statistical significance of 7.6σ. Fitting the structure $X(1840)$ with a modified Breit-Wigner function yields $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 and $\Gamma = 83 \pm 14 \pm 11$ MeV. The product branching fraction is determined to be $B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$. The comparison to the BESIII results of the masses and widths of the $X(1835)$ [4], $X(p\bar{p})$ [15], $X(1870)$ [14], and $X(1810)$ [16] are displayed in Fig. 3, where the mass of $X(1840)$ is in agreement with those of $X(1835)$ and $X(p\bar{p})$, while its width is significantly different from either of them. However, we do not include the BESII result in Fig. 3 as a more precise study of the $X(1835)$ in BESIII [4] indicates that one must consider the presence of additional resonances above 2 GeV/c^2 that were not apparent in the BESII analysis to obtain an accurate determination of the width of the $X(1835)$. Therefore, based on these data, one cannot determine whether $X(1840)$ is a new state or the signal of a $3(\pi^+\pi^-)$ decay mode of an existing state. Further study, including an amplitude analysis to determine the spin and parity of the $X(1840)$, is needed to establish the relationship between different experimental observations in this mass region and determine the nature of the underlying resonance or resonances.

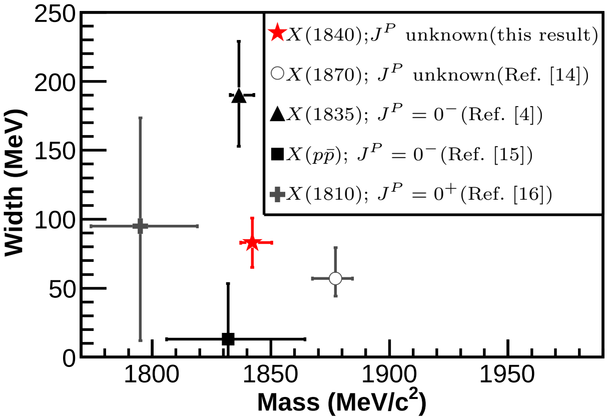

FIG. 3. Comparisons of observations at BESIII. The error bars include statistical, systematic, and, where applicable, model uncertainties.

A search for $\eta' \to 3(\pi^+\pi^-)$ is also performed, but no η' signal is observed. The upper limit on the branching fraction for the decay at the 90% confidence level is $B(\eta' \to 3(\pi^+\pi^-)) < 3.1 \times 10^{-5}$, which is improved by one order of magnitude compared to the previous measurement [28].

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