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Recent results on J/ψ radiative decays from BESIII

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Summary. — The BESIII detector has accumulated 1.31×10^9 J/ψ data samples. Based on this sample, the light hadron spectroscopy was extensively studied and many important progresses were achieved in these years. In this proceeding, the recent results on J/ψ radiative decays are reviewed, which include the spin-parity determination of the $X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$, the observation of the $X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$, the partial wave analysis of $J/\psi \to \gamma\phi\phi$ and the model independent partial wave analysis of $J/\psi \to \gamma\pi^0\pi^0$.

1. – Introduction

Quantum Chromodynamics (QCD) is used to describe the strong interactions of colored quarks and gluons, and it predicts the existence of the unconventional hadrons, such as glueballs, hybrid states and multiquark states. The search of these new kind of hadrons is one of the main interests in experimental particle physics.

The BESIII detector [1] is a magnetic spectrometer located at BEPCII, which is a double-ring e^+e^- collider with center-of-mass energies between 2.0 GeV and 4.6 GeV. The BESIII has accumulated $(1310.6 \pm 10.5) \times 10^6$ J/ψ events [2, 3] since 2009.

2. – Spin parity determination of the $X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

The $X(1835)$ was first observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ decays [4], and was subsequently confirmed by BESIII [5]. The discovery of the $X(1835)$ has stimulated many theoretical interpretations, such as a $p\bar{p}$ bound state [6], a glueball [7], or a radial excitation of the η' meson [8]. To understand the nature of the $X(1835)$, it is crucial to measure its spin parity and to search for its new decay modes.

Based on a sample of $(1310.6 \pm 10.5) \times 10^6$ [2, 3], the $X(1835)$ was observed in the $K_S^0 K_S^0 \eta$ mass spectrum in $J/\psi \to \gamma K_S^0 K_S^0 \eta$ process with a statistical significance greater than 12.9σ [9]. The $X(1835)$ structure can be seen in fig. 1(a). By performing a partial wave analysis (PWA) to the data, the $X(1835) \to K_S^0 K_S^0 \eta$ is found to be dominated by the $f_0(980)$ production, which can be seen in fig. 1(b).

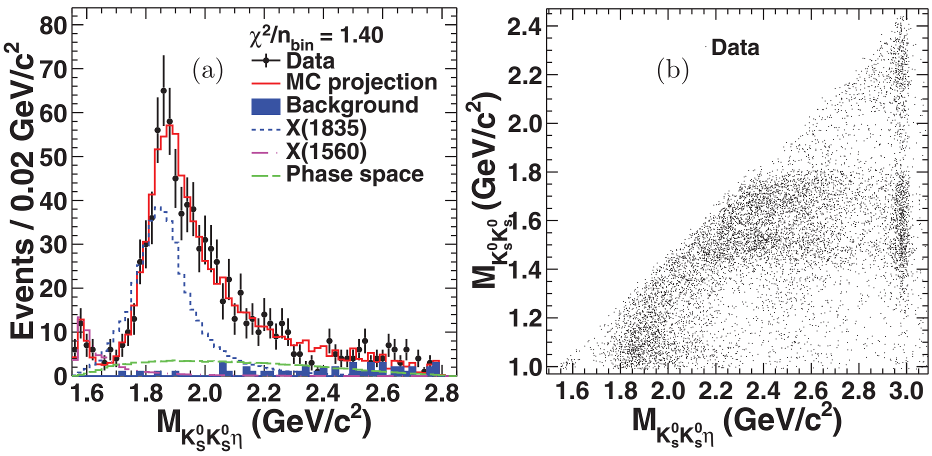

Fig. 1. – Distributions for the selected events: (a) invariant mass distribution of $K_S^0 K_S^0 \eta$. Dots with error bars are for data; the solid histogram is the PWA total fit projection; the shaded histograms is for the non-η backgrounds estimated by the η sideband; the short-dashed, dash-dotted and long-dashed histograms show the contributions of the $X(1835)$, the $X(1560)$ and the non-resonant component, respectively. (b) Scatter plot of $M_{K_S^0 K_S^0}$ *vs.* $M_{K_S^0 K_S^0 \eta}$.

The spin parity of the $X(1835)$ is determined to be 0^{-+}. The mass and width of the $X(1835)$ are measured to be $1844 \pm 9(stat.)^{+16}_{-25}(syst.)\,\mathrm{MeV}/c^2$ and $192^{+20}_{-17}(stat.)^{+62}_{-43}(syst.)\,\mathrm{MeV}$, respectively. The corresponding product branching fraction of $J/\psi \to \gamma X(1835)$ and $X(1835) \to K_S^0 K_S^0 \eta$ is measured to be $(3.31^{+0.33}_{-0.30}(stat.)^{+1.96}_{-1.29}(syst.)) \times 10^{-5}$. The mass and width of the $X(1835)$ are consistent with the values obtained from the decay of $J/\psi \to \gamma\pi^+\pi^-\eta'$ by BESIII [5].

Another 0^{-+} state, the $X(1560)$, is also observed in the data with a statistical significance larger than 8.9σ. The mass and width of the $X(1560)$ are measured to be $1565 \pm 8(stat.)^{+0}_{-63}(syst.)\,\mathrm{MeV}/c^2$ and $45^{+14}_{-13}(stat.)^{+21}_{-28}(syst.)$ MeV, respectively. The mass and width of the $X(1560)$ are consistent with those of the $\eta(1405)$ and $\eta(1475)$ as given in ref. [10] within 2.0σ and 1.4σ, respectively. Due to the low statistics, it is difficult to determine if the $X(1560)$ is the same state as the $\eta(1405)/\eta(1475)$ or a new meson.

3. – Observation of the $X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$

The $X(1835)$ was determined to be a pseudoscalar particle [5,9], 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.

The decay of $J/\psi \to \gamma 3(\pi^+\pi^-)$ was studied with a sample of 225.3×10^6 J/ψ events [2], and the $X(1840)$ was observed in the $3(\pi^+\pi^-)$ mass spectrum with a statistical significance of 7.6σ [11]. The mass spectrum of $3(\pi^+\pi^-)$ is shown in fig. 2. The mass and width of the $X(1840)$ is determined to be $1842.2 \pm 4.2(stat.)^{+7.1}_{-2.6}(syst.)\,\mathrm{MeV}/c^2$ and $83 \pm 14(stat.) \pm 11(syst.)\,\mathrm{MeV}$, respectively. The product branching fraction is determined to be $\mathcal{B}(J/\psi \to \gamma X(1840)) \times \mathcal{B}(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36(stat.)^{+0.60}_{-0.74}(syst.)) \times 10^{-5}$. The mass of the $X(1840)$ is in agreement with those of the $X(1835)$ [5] and the $X(p\bar{p})$ [12], while its width is significantly different from either of them.

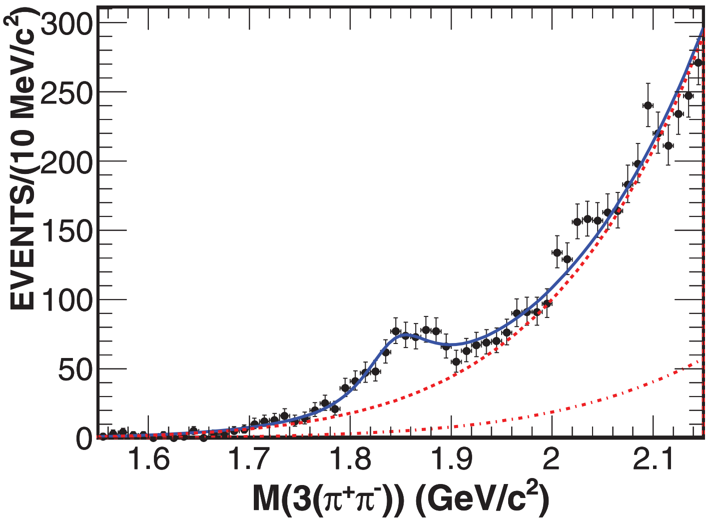

Fig. 2. – The fit of the mass spectrum of $3(\pi^+\pi^-)$. The dots with error bars are for data; the solid line is the fit result. The dashed line represents all the backgrounds, including the background events from $J/\psi \to \pi^0 3(\pi^+\pi^-)$ (represented by the dash-dotted line, fixed in the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

4. – Partial wave analysis of $J/\psi \to \gamma\phi\phi$

QCD predicts the existence of glueballs, and the search for glueballs is an important field of research in hadron physics. The lowest-lying glueballs are scalar (mass 1.5–1.7 GeV/c^2), tensor (mass 2.3–2.4 GeV/c^2), and pseudoscalar (mass 2.3–2.6 GeV/c^2) predicted by Lattice QCD [13]. The J/ψ radiative process is gluon rich and is therefore ideal for the search of glueballs.

In previous experiments, there were several observations in $\phi\phi$ system: the broad 2^{++} structures around 2.3 GeV/c^2 in $\pi^- N$ reactions [14] and in $p\bar{p}$ central collisions [15]; a tensor glueball was assumed to be mixed with conventional tensor resonances [16]; the $\eta(2225)$ was discovered in $J/\psi \to \gamma\phi\phi$ [17].

Based on $(1310.6 \pm 10.5) \times 10^6$ J/ψ events [2,3] collected with the BESIII detector, a PWA on $J/\psi \to \gamma\phi\phi$ was performed [18]. Figure 3(a) shows the projection of the PWA fit results, which is consistent with the model independent PWA fit as shown in fig. 3(b). Table I shows the components of the PWA fit results. The PWA results show that the $\phi\phi$ system is dominated by 0^{-+} contributions: the existence of the $\eta(2225)$ is confirmed and two additional pseudoscalar states, the $\eta(2100)$ and the X(2500), are observed. The new experimental results are helpful for mapping out pseudoscalar excitations and searching for a 0^{-+} glueball. The three tensors $f_2(2100)$, $f_2(2300)$ and $f_2(2340)$ observed in $\pi^- p \to \phi\phi n$ [14] are also observed in $J/\psi \to \gamma\phi\phi$. Recently, the production rate of the pure tensor glueball in J/ψ radiative decays has been predicted by Lattice QCD [19], which is compatible with the large production rate of the $f_2(2340)$ in $J/\psi \to \gamma\phi\phi$ and $J/\psi \to \gamma\eta\eta$ [20].

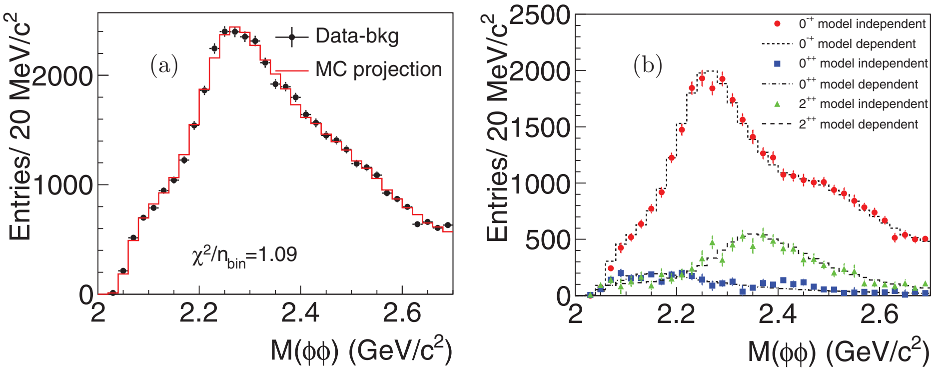

Fig. 3. – Superposition of data and the PWA fit projections for: (a) invariant mass distributions of $\phi\phi$; (b) intensities of individual J^{PC} components. The red dots, blue boxes and green triangles with error bars are the intensities of $J^{PC} = 0^{-+}$, 0^{++} and 2^{++}, respectively, from the model independent fit in each bin. The short-dashed, dash-dotted and long-dashed histograms show the coherent superpositions of the Breit-Wigner resonances with $J^{PC} = 0^{-+}$, 0^{++} and 2^{++}, respectively, from the model dependent fit.

5. – Amplitude analysis of $\pi^0\pi^0$ system produced in radiative J/ψ decays

The light isoscalar scalar meson spectrum ($I^G J^{PC} = 0^+0^{++}$) remains relatively poorly understood despite many years of investigation. While knowedege of the low mass scalar meson spectrum is important for several reasons. In particular, the lightest glueball state is expected to have scalar quantum numbers [13]. The low mass scalar meson spectrum is also of interest in probing the fundamental interactions of hadrons in that it allows for testing of chiral perturbation theory to one loop [21].

Conservation of parity in strong and electromagnetic interactions, along with the conservation of angular momentum, restricts the quantum numbers of the pseudoscalar-pseudoscalar pair produced in J/ψ radiative decays. Thus only amplitudes with even angular momentum and positive parity and charge conjugation quantum numbers are accessible ($J^{PC} = 0^{++}, 2^{++}, 4^{++}$, *etc.*).

Table I. – *Mass, width, $\mathcal{B}(J/\psi \to \gamma X \to \gamma\phi\phi)$ (B.F.) and significance (Sig.) of each component in the baseline solution. The first errors are statistical and the second ones are systematic.*

Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$2.40 \pm 0.10^{+2.47}_{-0.18}$	28 σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$3.30 \pm 0.09^{+0.18}_{-3.04}$	22 σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$0.17 \pm 0.02^{+0.02}_{-0.08}$	8.8 σ
$f_0(2100)$	2101	224	$0.43 \pm 0.04^{+0.24}_{-0.03}$	24 σ
$f_2(2010)$	2011	202	$0.35 \pm 0.05^{+0.28}_{-0.15}$	9.5 σ
$f_2(2300)$	2297	149	$0.44 \pm 0.07^{+0.09}_{-0.15}$	6.4 σ
$f_2(2340)$	2339	319	$1.91 \pm 0.14^{+0.72}_{-0.73}$	11 σ
0^{-+} PHSP			$2.74 \pm 0.15^{+0.16}_{-1.48}$	6.8 σ

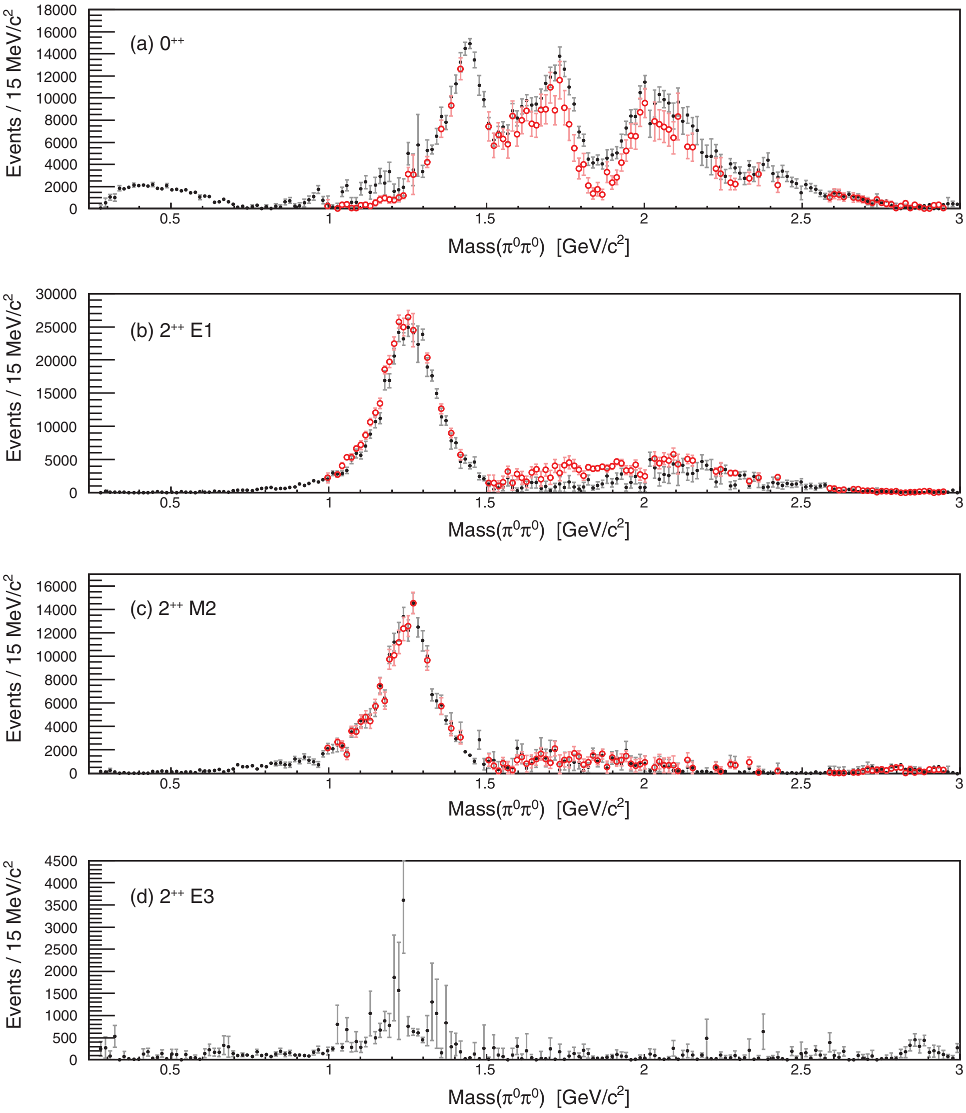

Fig. 4. – The intensities for the (a) 0^{++}, (b) 2^{++} E1, (c) 2^{++} M2 and (d) 2^{++} E3 amplitudes as a function of $M_{\pi^0\pi^0}$ for the nominal results. The solid black markers show the intensity calculated from one set of solutions, while the open red markers represent its ambiguous partner. Note that the intensity of the 2^{++} E3 amplitude is redundant for the two ambiguous solutions. Only statistical errors are presented.

In the mass independent amplitude analysis of $\pi^0\pi^0$ system [22], the components of the $\pi\pi$ amplitude independently for many small regions of $\pi\pi$ invariant mass are measured based on $(1.311 \pm 0.011) \times 10^9$ J/ψ decays [2, 3] collected with the BESIII detector, and a piecewise complex function from the measurements that describes the s-dependence of the $\pi\pi$ dynamics is constructed. The intensity for each amplitude as a function of $M_{\pi^0\pi^0}$ is plotted in fig. 4. Each of the phase differences with respect to the

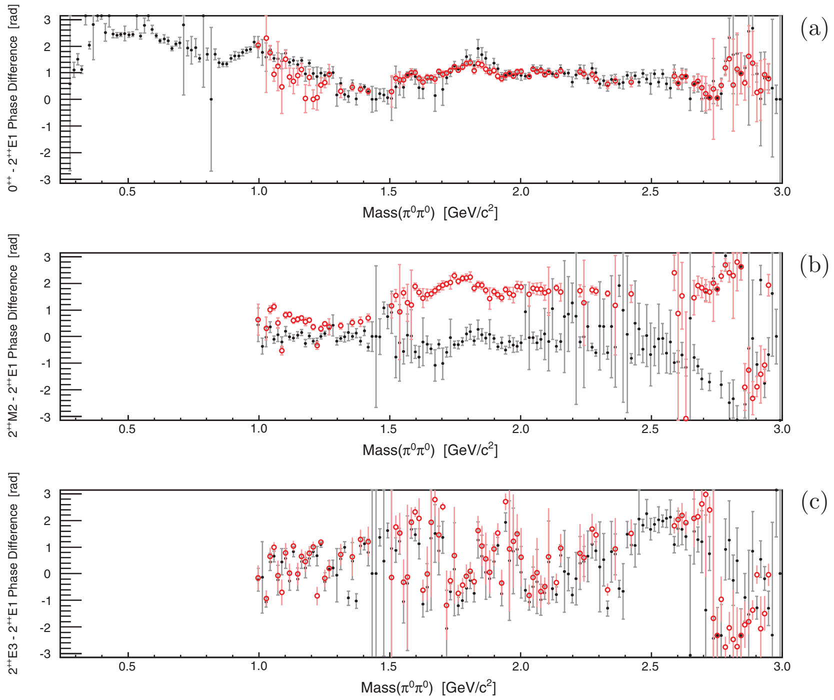

Fig. 5. – The phase differences relative to the reference amplitude (2^{++} E1) for the (a) 0^{++}, (b) 2^{++} M2 and (c) 2^{++} E3 amplitudes as a function of $M_{\pi^0\pi^0}$ for the nominal results. The solid black markers show the phase differences calculated from one set of solutions, while the open red markers represented the ambiguous partner solutions. An arbitrary phase convention is applied here in which the phase difference between the 0^{++} and 2^{++} E1 amplitudes is required to be positive. Only statistical errors are presented.

reference amplitude (2^{++} E1), which is constrained to be real, is plotted in fig. 5. Above the $K\bar{K}$ threshold, two distinct sets of solutions are apparent in most bins as expected.

The results of the mass independent analysis exhibit significant structures in the 0^{++} and 2^{++}, while the 4^{++} contribution is negligible. Finally, the branching fraction of radiative J/ψ decays to $\pi^0\pi^0$ is measured to be $(1.15 \pm 0.05) \times 10^{-3}$, where the error is systematic only and the statistical error is negligible.

6. – Summary

Based on full or part of the 1.31×10^9 J/ψ events collected with the BESIII detector, analyses of $J/\psi \to \gamma K^0_S K^0_S \eta$, $J/\psi \to \gamma 3(\pi^+\pi^-)$, $J/\psi \to \gamma\phi\phi$ and $J/\psi \to \gamma\pi^0\pi^0$ were performed, and the results are reviewed in this proceeding. The spin parity of the $X(1835)$ is determined to be 0^{-+} by performing a PWA of $J/\psi \to \gamma K^0_S K^0_S \eta$; the $X(1840)$ is observed in $J/\psi \to \gamma 3(\pi^+\pi^-)$ with a statistical significance greater than 7.6 σ; the PWA results of $J/\psi \to \gamma\phi\phi$ and $J/\psi \to \gamma\pi^0\pi^0$ are also presented.

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