Recent Results on Hadron Spectroscopy from BESIII

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Abstract. Hadron spectroscopy is one of the most important physics goals of BESIII. BESIII brings great opportunities to study the XYZ states of charmonium by directly producing the Y states up to 4.6 GeV. High statistics of charmonium decays collected at BESIII provide an excellent place for hunting gluonic excitations and studying the excited baryons. Recent results of light hadron spectroscopy and charmonium spectroscopy from BESIII will be reported.

INTRODUCTION

Hadron spectroscopy is a unique way to access Quantum Chromodynamics (QCD). QCD-motivated models for hadrons predict an assortment of “Exotic Hadrons” that have structures that are more complex than the quark-antiquark mesons and three-quark baryons of the original quark model, such as glueballs, hybrids and multi-quark states. Experimental search of these predictions and subsequent investigation of their properties would provide validation of and valuable input to the quantitative understanding of QCD.

BESIII (Beijing Spectrometer) is a general purpose 4π detector at the upgraded BEPCII (Beijing Electron and Positron Collider) that operated in the τ-charm threshold energy region[1]. Since 2009, it has collected the world’s largest data samples of J/ψ, ψ(3686), ψ(3770) and ψ(4040) decays. More recently, data were taken in the energy region above 4 GeV, where energies up to about 4.6 GeV are accessible. These data are being used to make a variety of interesting and unique studies of light hadron spectroscopy, charmonium spectroscopy, high-statistics measurements of charmonium decays and D meson decays.

Charmonium spectroscopy

The quark model [2], which treats mesons as combinations of one quark and one anti-quark, is very successful in describing meson properties, particularly in the charmonium (c⃗c) region below the open-charm threshold. [3]. The past decade, however, has seen the discovery of a number of new states (named the XYZ states) that do not fit within this model, and which perhaps point towards more complex systems. With its unique data samples at energies of 3.8–4.6 GeV, the BESIII experiment made a significant contribution to the study of charmonium and charmonium-like states.

Charged charmonium-like states: Zc’s

Recently, in the study of e+e− → J/ψπ−, a distinct charged structure, named the Zc(3900)+, was observed in the J/ψπ+ spectrum by BESIII [4] and Belle [5]. Its existence was confirmed shortly thereafter with CLEO-c data [6]. The existence of the neutral counterpart in the decay Zc(3900)0 → J/ψπ0 has also been reported in CLEO-c data [6] and by BESIII [7], thus complementing the isospin-triplet representation of isospin one, I = 1, resonances. The Zc(3900) is a good candidate for an exotic state beyond simple quark models, since it contains a c⃗c pair and is also electrically charged. Noting that the Zc(3900) has a mass very close to the D∗D threshold (3875 MeV), BESIII analyzed the process e+e− → π±(D∗D)+, and a clear structure in the (D∗D)+ mass spectrum is seen, called the Zc(3885). The measured mass and width are (3883.9 ± 1.5 ± 4.2) MeV/c² and (24.8 ± 3.3 ± 11.0) MeV, respectively, and quantum
numbers $J^P = 1^+$ are favored [8]. A neutral structure in the $D\bar{D}^*$ system around the $D\bar{D}^*$ mass threshold is observed with a statistical significance greater than 10σ in the processes $e^+e^- \rightarrow D^*\bar{D}^*\pi^0 + \text{c.c.}$ and $e^+e^- \rightarrow D^*\bar{D}^*\pi^0 + \text{c.c.}$ at $\sqrt{s} = 4.226$ and 4.257 GeV in the BESIII experiment [10]. Assuming the $Z_c(3885) \rightarrow D\bar{D}^*$ and the $Z_c(3900) \rightarrow J/\psi\pi$ signals are from the same source, the ratio of partial widths $\Gamma(Z_c(3885)\rightarrow D\bar{D}^*)/\Gamma(Z_c(3900)\rightarrow J/\psi\pi)$ is determined to be $6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold.

Figure 1 shows the reactions:

\begin{equation}
\text{Table 1 lists corresponding masses and widths of the } Z_c \text{ states near the } D^*\bar{D}^* \text{ threshold.}
\end{equation}

BESIII analyzed the reaction $e^+e^- \rightarrow \pi^+\pi^- h_c$, at $E_{CM} = 4.23, 4.26$ and 4.36 GeV [11]. Corresponding $\pi^+h_c$ invariant mass distribution, when all energy points are combined, is shown in Fig. 3. The $Z_c(4020)^+$ signal has $8.9\sigma$ significance. And the inset represents a search for the $Z_c(3900) \rightarrow \pi^0 h_c$, at $E_{CM} = 4.23$ and 4.26 GeV. At the 90% confidence level (C.L.), the upper limits on the production cross-sections are set to $\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^+) < 13 \text{ pb}$ at 4.23 GeV and < 11 pb at 4.26 GeV. These are lower than those of $Z_c(4020) \rightarrow \pi^+ J/\psi$ [4]. BESIII also observed $e^+e^- \rightarrow \pi^0 h_c$ at $\sqrt{s} = 4.23, 4.26$, and 4.36 GeV [12], confirming the isospin of $Z_c(4020)$ to be one. Similarly to the case of the $Z_c(3900)$, the mass of the $Z_c(4020)$ is near the threshold for $D^*\bar{D}^*$ production. BESIII studied two reactions: $e^+e^- \rightarrow (D^*\bar{D}^*)^0\pi^0$, at $E_{CM} = 4.26$ GeV [14], and $e^+e^- \rightarrow (D^*\bar{D}^*)^0\pi^0$, at $E_{CM} = 4.23$ and 4.26 GeV [15]. A structure that couples to $D^*\bar{D}^*$ is evident, in both charged and neutral decays, denoted as $Z_c(4025)$. Fig. 4 shows the results of $Z_c(4025)$. Assuming the $Z_c(4020)$ and the $Z_c(4025)$ signals are from the same source, the ratio of partial widths $\Gamma(Z_c(4025)\rightarrow D^*\bar{D}^*)/\Gamma(Z_c(4020)\rightarrow h_c\pi)$ is determined to be $12 \pm 5$. Table 1 lists corresponding masses and widths of the $Z_c$ states near the $D^*\bar{D}^*$ threshold.

**FIGURE 1.** $Z_c(3900) \rightarrow \pi J/\psi$ production in $e^+e^- \rightarrow \pi\pi J/\psi$ processes: (a) $Z_c(3900)^+ \rightarrow \pi^+ J/\psi$ [4], (b) $Z_c(3900)^0 \rightarrow \pi^0 J/\psi$ [7].

**FIGURE 2.** $Z_c(3885) \rightarrow (D\bar{D}^*)^*$ production in $e^+e^- \rightarrow \pi(D\bar{D}^*)$ processes: (a) $Z_c(3885)^+ \rightarrow (D\bar{D}^*)^+ \pi^0$ [8], (b) $Z_c(3885)^0 \rightarrow D^*\bar{D}^*$ [10].
Observation of $Y(4260) \rightarrow \gamma X(3872)$

BESIII observed $e^+ e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+ \pi^- J/\psi$, with $J/\psi$ reconstructed through its decays into lepton pairs ($\ell^+ \ell^- = e^+ e^- \text{ or } \mu^+ \mu^-$) [16]. The $M(\pi^+ \pi^- J/\psi)$ distribution (summed over all energy points), as shown in Fig. 5 (left), was fitted to extract the mass and signal yield of $X(3872)$. The Born-order cross-section was measured. The energy-dependent cross-sections were fitted with a $Y(4260)$ resonance (parameters fixed to PDG [32] values), linear continuum, or $E1$-transition phase space ($\propto E_1^2$) term, as shown in Figure 5 (right). The measurements are consistent with expectations for the radiative transition process $Y(4260) \rightarrow \gamma X(3872)$. Combining the above with the $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ cross-section measurement at $\sqrt{s} = 4.26$ GeV from BESIII [4], we obtain $\sigma^{\gamma}[e^+ e^- \rightarrow \gamma X(3872)] \cdot B[X(3872) \rightarrow \pi^+ \pi^- J/\psi]/\sigma^{\gamma}[e^+ e^- \rightarrow \pi^+ \pi^- J/\psi] = (5.2 \pm 1.9) \times 10^{-3}$, under the assumption that $X(3872)$ and $\pi^+ \pi^- J/\psi$ are only produced from $Y(4260)$ decays. If we take $B[X(3872) \rightarrow \pi^+ \pi^- J/\psi] = 5\%$ [17], then $\mathcal{R} = \frac{B[Y(4260) \rightarrow \gamma X(3872)]}{B[Y(4260) \rightarrow \pi^+ \pi^- J/\psi]} = 0.1$.

Observation of $\psi(1^3D_2)$

BESIII observed $X(3823)$ in the $e^+ e^- \rightarrow \pi^+ \pi^- X(3823) \rightarrow \pi^+ \pi^- \chi_{c1}$ process with a statistical significance of 6.2$\sigma$ in data samples at c.m. energies of $\sqrt{s} = 4.23, 4.26, 4.36, 4.42, \text{ and } 4.60$ GeV [18]. The measured mass of the $X(3823)$ is $(3821.7 \pm 1.3 \pm 0.7)$ MeV$/c^2$, and the width is less than 16 MeV at the 90$\%$ confidence level. The products of the Born cross sections for $e^+ e^- \rightarrow \pi^+ \pi^- X(3823)$ and the branching ratio $B[X(3823) \rightarrow \gamma \chi_{c1,2}]$ are also measured. These measurements are in good agreement with the assignment of the $X(3823)$ as the $\psi(1^3D_2)$ charmonium state. The fitted results to $\pi^+ \pi^-$ recoil mass distributions for events in the $\chi_{c1}$ and $\chi_{c2}$ signal regions are shown in Fig. 6 (a) and Fig. 6 (b), respectively.

The production cross-sections of $\sigma^{\gamma}[e^+ e^- \rightarrow \pi^+ \pi^- X(3823)] \cdot B[X(3823) \rightarrow \gamma \chi_{c1,2}]$ were also measured at these c.m. energies. The cross-sections of $e^+ e^- \rightarrow \pi^+ \pi^- X(3823)$ were fitted with the $Y(4360)$ shape or the $\psi(4415)$ shape, as shown in Fig. 6 (c). Both the $Y(4360)$ and $\psi(4415)$ hypotheses are accepted at a 90$\%$ C.L.
TABLE 1. Masses and widths of exotic meson candidates studied by BESIII.

| Decay           | Mass [MeV/c²] | Width [MeV] | Ref.   |
|-----------------|---------------|-------------|--------|
| Zₐ(3900)* → π⁺J/ψ | 3899.0±3.6±4.9 | 46±10±20   | [4]    |
| Zₐ(3900)⁰ → n⁺J/ψ | 3894.8±2.3±3.2 | 29.6±8.2±8.2 | [7]    |
| Zₐ(3885)* → (D⁺D⁻)⁺ (single D-tag) | 3883.9±1.5±4.2 | 24.8±3.3±11.0 | [8]    |
| Zₐ(3885) → (D⁺D⁻)⁺ (double D-tag) | 3881.7±1.6±2.1 | 26.6±2.0±2.3 | [13]   |
| Zₐ(3885)⁰ → (D⁺D⁻)⁰ | 3885.7⁺1.3⁻1.2±9.4 | 35⁺11⁻12±15 | [10]   |
| Zₐ(4020)* → π⁺hᶜ | 4022.9±0.8±2.7 | 7.9±2.7±2.6 | [11]   |
| Zₐ(4020)⁰ → n⁺hᶜ | 4023.9±2.2±3.8 fixed |          | [12]   |
| Zₐ(4025)* → (D⁺D⁻)⁺ | 4026.3±2.6±3.7 | 24.8±5.6±7.7 | [14]   |
| Zₐ(4025)⁰ → (D⁺D⁻)⁰ | 4025.5⁺2.0⁻1.9±3.1 | 23.0±6.0±1.0 | [15]   |

FIGURE 5. (a) Fit to the M(π⁺π⁻J/ψ) distribution observed at BESIII. Dots with error bars are data, the curves are the best fit. (b) Fit to $\sigma(\gamma\gamma \rightarrow \eta X(3872)) \times B[X(3872) \rightarrow \pi⁺\pi⁻J/ψ]$ measured by BESIII with a Y(4260) resonance (red solid curve), a linear continuum (blue dashed curve), or an $E1$-transition phase space term (red dotted-dashed curve). Dots with error bars are data.

**Structures in $e^+e^- \rightarrow$ charmonium + hadrons**

The $e^+e^- \rightarrow \omega_{Y(0)}$ process was observed at $\sqrt{s} = 4.23$ and 4.26 GeV for the first time [19]. By examining the $\omega_{Y(0)}$ cross section as a function of center-of-mass energy as shown in Fig. 7 (a), we find that it is inconsistent with the line shape of the Y(4260) observed in $e^+e^- \rightarrow \pi⁺\pi⁻J/ψ$. Assuming the $\omega_{Y(0)}$ signals come from a single resonance, we extract mass and width of the resonance to be (4230 ± 8 ± 6) MeV/c² and (38 ± 12 ± 2) MeV, respectively, and the statistical significance is more than 9σ.

BESIII analyzed $e^+e^- \rightarrow \eta J/ψ$ [20]. Statistically significant $\eta$ signals were observed, and the corresponding Born cross-sections were measured. The Born cross-sections $\sigma(e^+e^- \rightarrow \eta J/ψ)$ in this measurement are well consistent with previous results [21, 22]. The measured Born cross-sections were also compared to those of $e^+e^- \rightarrow \pi⁺\pi⁻J/ψ$ obtained from the Belle experiment [23], as shown in Fig. 7 (b). Different line shapes can be observed in these two processes, indicating that the production mechanism of $\eta J/ψ$ differs from that of $\pi⁺\pi⁻J/ψ$ in the vicinity of $\sqrt{s} = 4.1–4.6$ GeV. This could indicate the existence of a rich spectrum of the Y states in this energy region with different coupling strengths to various decay modes.

**Light meson spectroscopy**

Glueballs and other resonances with large gluonic components are predicted as bound states by QCD. The lightest (scalar) glueball is estimated to have a mass in the range from 1 to 2 GeV/c²; pseudoscalar and tensor glueballs are expected at higher masses. Radiative decays of the charmonium provide a gluon rich environment and are therefore regarded as one of the most promising hunting grounds for glueballs and hybrids.
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$

$X(1835)$ was first observed in $J/\psi \rightarrow \gamma p\bar{p}$ by BESII [25]; this observation was subsequently confirmed by BESIII [26]. In addition, an enhancement in the invariant $p\bar{p}$ mass at threshold, $X(p\bar{p})$, was first observed by BESII in the decay $J/\psi \rightarrow \gamma p\bar{p}$ [27], and was later also seen by BESIII [28] and CLEO [29]. In a partial wave analysis (PWA), BESIII determined the $J^{PC}$ of the $X(p\bar{p})$ to be $0^+$ [30]. The mass of the $X(p\bar{p})$ is consistent with $X(1835)$, but the width of the $X(p\bar{p})$ is significantly narrower. To understand the nature of the $X(1835)$, it is crucial to measure its $J^{PC}$ and to search for new decay modes. Fig. ?? (a) shows the scatter plot of the invariant mass of $K_S^0 K_S^0$ versus that of $K_S^0 K_S^0 \eta$, indicating the structure around 1.85 GeV/c$^2$ is strongly correlated with $f_0(980)$. A partial wave analysis (PWA) of $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$ has been performed in the mass range $M_{K_S^0 K_S^0 \eta} < 2.8$ GeV/c$^2$ after requiring $M_{K_S^0 K_S^0} < 1.1$ GeV/c$^2$ [31]. Fig. 8 (b) and (c) are the invariant mass distributions of $K_S^0 K_S^0 \eta$, $K_S^0 K_S^0$. Overlaid on the data are the PWA fit projections, as well as the individual contributions from each component. The PWA fit requires a contribution from $X(1835) \rightarrow K_S^0 K_S^0 \eta$ with a statistical significance greater than 12.9σ, where the $X(1835) \rightarrow K_S^0 K_S^0 \eta$ is dominated by $f_0(980)$ production. 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) $^{+23}_{-29}$ (syst) MeV/c$^2$ and $192^{+17}_{-17}$ (stat) $^{+43}_{-43}$ (syst) MeV, respectively. The corresponding product branching fraction $B_{X(1835)}$ is measured to be $(3.31^{+0.33}_{-0.30} \pm 0.19)$ (stat) $^{+1.06}_{-1.29}$ (syst) $\times 10^{-5}$. The mass and width of the $X(1835)$ are consistent with the values obtained from the decay $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ by BESIII [26]. These results are all first-time measurements and provide important information to further understand the nature of the $X(1835)$. Another $0^+$ state, the $X(1560)$, also is observed in data with a statistical significance larger than 8.9σ. The mass and width of the $X(1560)$ are consistent with those of the $\eta(1405)$ and $\eta(1475)$ as given in Ref. [32] within 2.0σ and 1.4σ.
consequently, permits the development of dynamical models or parameterizations for the data.

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\text{FIGURE 8.} \quad \text{(a) scatter plot of } M_{K^0K^0} \text{ versus } M_{K^0^*K^0}. \quad \text{Comparisons between data and PWA fit projections. (b), and (c) are the invariant mass distributions of } K^0_S K^0_S \eta, K^0_S K^0. \quad \text{Dots with error bars are data; the shaded histograms are the non-}\eta \text{ backgrounds estimated by the } \eta \text{ sideband; the solid histograms are phase space MC events of } J/\psi \rightarrow \gamma K^0_S K^0_S \eta \text{ with arbitrary normalization.}
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Amplitude analysis of the \( \pi^0 \pi^0 \) system produced in radiative \( J/\psi \) decays

A mass independent amplitude analysis of the \( \pi^0 \pi^0 \) system in radiative \( J/\psi \) decays is performed [33]. This analysis uses the world’s largest data sample of its type, collected with the BESIII detector, to extract a piecewise function that describes the scalar and tensor \( \pi \pi \) amplitudes in this decay. While the analysis strategy employed to obtain results has complications, namely ambiguous solutions, a large number of parameters, and potential bias in subsequent analyses from non-Gaussian effects, it minimizes systematic bias arising from assumptions about \( \pi \pi \) dynamics, and, consequently, permits the development of dynamical models or parameterizations for the data.

The intensities and phase differences for the amplitudes in the fit are presented as a function of \( M_{\phi'\phi'} \) in Ref. [33]. Additionally, in order to facilitate the development of models, the intensities and phases for each bin of \( M_{\phi'\phi'} \) are given in supplemental materials of Ref. [33]. These results may be combined with those of similar reactions for a more comprehensive study of the light scalar meson spectrum. Finally, the branching fraction of radiative \( J/\psi \) 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. This is the first measurement of this branching fraction.

Partial Wave Analysis of \( J/\psi \rightarrow \gamma \phi \phi \)

The low lying pseudoscalar glueball is predicted to be around 2.3–2.6 GeV/c\(^2\) by Lattice QCD [34, 35, 36]. Aside from the \( \eta'(2225) \), very little is known in the pseudoscalar sector above 2 GeV/c\(^2\). A partial wave analysis of the decay \( J/\psi \rightarrow \gamma \phi \phi \) is performed in order to study the intermediate states. The most remarkable feature of the PWA results is that 0\(^+\) states are dominant. The existence of the \( \eta'(2225) \) is confirmed and two additional pseudoscalar states, \( \eta(2100) \) with a mass 2050\(^{+30+77}\) MeV/c\(^2\) and a width 250\(^{+36+187}\) MeV/c\(^2\) and \( X(2500) \) with a mass 2470\(^{+15+63}\) MeV/c\(^2\) and a width 230\(^{+64+51}\) MeV/c\(^2\), are observed. The new experimental results are helpful for mapping out pseudoscalar excitations and searching for a 0\(^+\) glueball. The three tensors \( f_2(2300) \) and \( f_2(2340) \) observed in \( \pi^+ p \rightarrow \phi \phi n \) [37] are also observed in \( J/\psi \rightarrow \gamma \phi \phi \). Recently, the production rate of the pure gauge tensor glueball in \( J/\psi \) radiative decays has been predicted by Lattice QCD [38], which is compatible with the large production rate of the \( f_2(2340) \) in \( J/\psi \rightarrow \gamma \phi \phi \) and \( J/\psi \rightarrow \gamma \eta \eta \) [39]. Fig. 9 shows the PWA fit results with comparison of data.

Light baryon spectroscopy

The \( J/\psi \) and \( \psi' \) experiments at BES provide an excellent place for studying excited nucleons and hyperons – \( N^*, \Lambda^*, \Sigma^* \) and \( \Xi^* \) resonances [40]. Complementary to other facilities, the baryon program at BES3 has several advantages [40]. For instance, \( \pi N \) and \( \pi \pi N \) systems from \( J/\psi \rightarrow \bar{N}N\pi \) and \( NN\pi \pi \) processes have an isospin of 1/2 due to isospin conservation; \( \psi \) mesons decay to baryon-antibaryon pairs through three or more gluons, where is a favorable place for producing hybrid (qqqq) baryons, and for searching some “missing” \( N^* \) resonances which have weak coupling to both \( \pi N \) and \( \gamma N \), but stronger coupling to \( g^3N \). Recently, in a partial wave analysis of \( \psi(3686) \rightarrow p\bar{p}N^0 \) [41], two new \( N^* \)
resonances $N(2300)$ and $N(2570)$ are observed with $J^P$ assignment of $1/2^+$ and $5/2^-$, respectively. In the studies of the decays of $\psi(3686) \to K^-\Lambda\bar{\Sigma}^+ + c.c.$ and $\psi(3686) \to \gamma K^-\Lambda\bar{\Sigma}^+ + c.c.$, two hyperons, $\Xi(1690)^-$ and $\Xi(1820)^-$, are observed in the $K^-\Lambda$ invariant mass distribution in the decay $\psi(3686) \to K^-\Lambda\bar{\Sigma}^+ + c.c.$ with significance of $4.9\sigma$ and $6.2\sigma$, respectively. The results are shown in shown in Fig. 9b. The branching fractions of $\psi(3686) \to K^-\Lambda\bar{\Sigma}^+ + c.c.$, $\psi(3686) \to K^-\Sigma^0\bar{\Sigma}^+ + c.c.$, $\psi(3686) \to \gamma\chi_{cJ} \to \gamma K^-\Lambda\bar{\Sigma}^+ + c.c.$ ($J = 0, 1, 2$), and $\psi(3686) \to \Xi(1690/1820)^-\bar{\Sigma}^+ + c.c.$ with subsequent decay $\Xi(1690/1820)^- \to K^-\Lambda$ are measured.

Summary

With the worlds largest samples of $J/\psi$, $\psi(3686)$, $\psi(3770)$, $Y(4260)$ etc from $e^+e^-$ production, the BESIII experiment made a significant contribution to the study of the charmonium spectroscopy, light meson spectroscopy and light baryon spectroscopy. BESIII will continue to run 6–8 years. Complementary to other experiments, with various production mechanisms, BESIII will continue shedding light on the the nature of hadrons.

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This work
Events / 15 MeV/c

| Mass (GeV/c) |
|-------------|
| 0           |
| 0.5         |
| 1           |
| 1.5         |
| 2           |
| 2.5         |
| 3           |

(a) 0++

(b) 2++

(c) 2++

(d) 2++

\(\chi^2/\text{nbin}=2.25\)