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Spectroscopy including XYZ states at BESIII

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With the unique e^+e^- data samples at energies between 3.8 and 4.6 GeV, significant contributions on the charmonium and charmonium-like states (i.e. XYZ states) are made by BESIII. We review the recent studies of the XYZ states at BESIII. These results include the observations of $e^+e^- \to \gamma X(3872)$ and $e^+e^- \to \pi^+\pi^- X(3823)$, the discovery of the Z_c family and the measurements of the hadron plus charmonium channels in e^+e^- annihilation which provide oppotunities for the investigation of the vector exotic Y states and connections between these XYZ states.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

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PoS(BEAUTY2016)053

1. Introduction

Numerous new charmonium and charmonium-like states were observed at B-factories in the last decades [1]. Some of them are good charmonium candidates, while many of them are not. Many interpretations are proposed for the nature of these exotic states [2], i.e. XYZ states. But there are still many open questions which need further studies, both experimentally and theoretically.

The BESIII [3] experiment at BEPCII is designed to collect e^+e^- collision data in the τ-charm energy region. BESIII has also collected data samples for XYZ studies at higher energy points, especially around the known vector charmonium or charmonium-like states like $\psi(4040)$, $\mathrm{Y}(4260)$, $\mathrm{Y}(4360)$, $\psi(4415)$ and $\mathrm{Y}(4660)$ [5, 6]. A large data sample at 4.18 GeV which is near $\psi(4170)$ was taken in 2016.

2. Studies of X states at BESIII

2.1 Observation of $e^+e^- \to \gamma\mathrm{X}(3872)$

With the data samples at 4.009 GeV, 4.230 GeV, 4.260 GeV and 4.360 GeV, BESIII observed for the first time the process $e^+e^- \to \gamma\mathrm{X}(3872)$ with $\mathrm{X}(3872) \to \pi^+\pi^- J/\psi$ [7]. The invariant mass of $\pi^+\pi^- J/\psi$ for $\mathrm{X}(3872)$ candidates is shown in Fig. 1 (left). The statistical significance of $\mathrm{X}(3872)$ is 6.3σ and the measured mass is $(3871.9 \pm 0.7 \pm 0.2)$ MeV/c^2 where the first uncertainty is statistical and the second systematic. A width of $(0.0^{+1.7}_{-0.0})$ MeV or less than 2.4 MeV at the 90% C.L. was obtained by a fit with a floating width. These results are consistent with previous measurements [8]. The measured Born cross section $\sigma^B(e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi)$ is shown in Fig. 1 (right) which supports strongly the existence of the radiative transition process $\mathrm{Y}(4260) \to \gamma\mathrm{X}(3872)$.

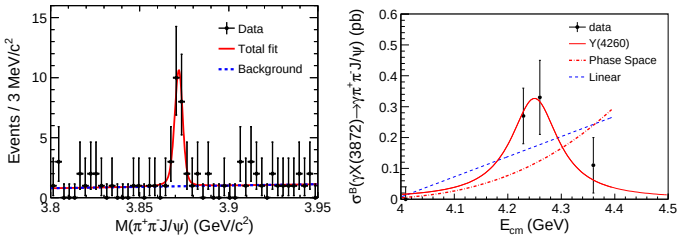

Figure 1: Left: Fit of the $M(\pi^+\pi^- J/\psi)$ distribution of a MC simulated histogram convolved with a Gaussian function for signal and a linear background function. Right: The fit to $\sigma^B(e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi)$ with a $\mathrm{Y}(4260)$ resonance (red solid curve), a linear continuum (blue dashed curve), or a E1-transition phase space term (red dotted-dashed curve). Dots with error bars are data.

2.2 Observation of $e^+e^- \to \pi^+\pi^-\mathrm{X}(3823)$

With the data samples at c.m. energies 4.230, 4.260, 4.360, 4.420, and 4.600 GeV, BESIII observed the $\mathrm{X}(3823)$ in the process $e^+e^- \to \pi^+\pi^-\mathrm{X}(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ with a statistical significance of 6.2σ [9]. The $\pi^+\pi^-$ recoil mass distributions for the event candidates in the χ_{c1} and χ_{c2} signal regions are shown in Fig 2 (left and middle). There is a clear $\mathrm{X}(3823)$ signal in the $\gamma\chi_{c1}$

mode, but not in the $\gamma\chi_{c2}$ mode. The measured mass and width are consistent with these of Belle experiment [10] and indicate X(3823) is a good candidate for the $\psi(1^3D_2)$ charmonium state [9]. The cross sections are also measured as shown in Fig 2 (right) for $e^+e^- \to \pi^+\pi^-$X(3823) $\to \pi^+\pi^-\gamma\chi_{c1}$, which can not distinguish between the Y(4360) decay and $\psi(4415)$ decay hypotheses.

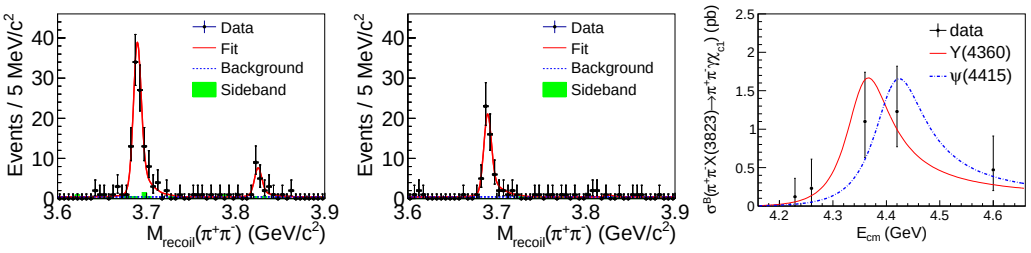

Figure 2: Left and middle: simultaneous fit to the $M_{\rm recoil}(\pi^+\pi^-)$ distribution of $\gamma\chi_{c1}$ events (left) and $\gamma\chi_{c2}$ events (middle), respectively. Right: Comparison of the energy-dependent cross sections of $e^+e^- \to \pi^+\pi^-$X(3823) $\to \pi^+\pi^-\gamma\chi_{c1}$ to the Y(4360) and $\psi(4415)$ line shapes.

3. Discovery of the Z_c family

BESIII contributed significantly on the discovery of the Z_c family which is summarized in Table 1.

Table 1: The summary of the measured mass, width, the decay mode and references for the Z_c states observed by BESIII.

Z_c	mass (MeV/c^2)	width (MeV)	decay mode	references
$Z_c(3900)^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^\pm J/\psi$	[11]
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	[13]
$Z_c(3885)^\pm$	$3882.3 \pm 1.1 \pm 1.9$	$26.5 \pm 1.7 \pm 2.3$	$(D\bar{D}^*)^\pm$	[14] [15]
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	[16]
$Z_c(4020)^\pm$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^\pm h_c$	[17]
$Z_c(4020)^0$	$4023.8 \pm 2.2 \pm 3.8$	Fixed to 7.9	$\pi^0 h_c$	[18]
$Z_c(4025)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$(D^*\bar{D}^*)^\pm$	[19]
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$(D^*\bar{D}^*)^0$	[20]

3.1 $Z_c(3900)$ and $Z_c(3885)$

A structure, which is refereed to as the $Z_c(3900)^\pm$, was first observed in the $\pi^\pm J/\psi$ mass spectrum of the process $e^+e^- \to \pi^+\pi^- J/\psi$ at 4.26 GeV by BESIII [11] and of the process $e^+e^- \to \gamma_{ISR}$Y(4260) $\to \gamma_{ISR}\pi^+\pi^- J/\psi$ by Belle [12]. A neutral partner, $Z_c(3900)^0$, was observed in the process $e^+e^- \to \pi^0\pi^0 J/\psi$ between the c.m. energy 4.19 and 4.42 GeV at BESIII [13]. The signals of $Z_c(3900)^\pm$ and $Z_c(3900)^0$ are shown in Fig 3.

As the mass of $Z_c(3900)$ is just above the $D\bar{D}^*$ mass threshold, BESIII studied $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ and observed a structure $Z_c(3885)^\pm$ in the $(D\bar{D}^*)^\pm$ mass spectrum [14, 15]. A neutral partner $Z_c(3885)^0$ was also observed in the process $e^+e \to (D\bar{D}^*)^0\pi^0$ [16].

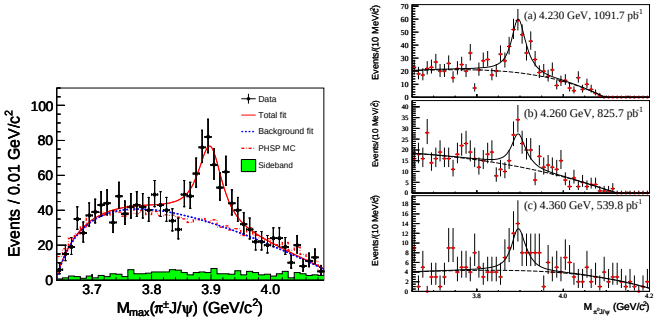

Figure 3: Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histograms are the phase space distributions and the shaded histograms are the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands.

3.2 $Z_c(4020)$ and $Z_c(4025)$

A structure $Z_c(4020)^{\pm}$ was observed by BESIII in the $\pi^{\pm}h_c$ mass spectrum of the process $e^+e^- \to \pi^+\pi^- h_c$ at c.m. energies of 3.90 to 4.42 GeV [17]. A neutral partner was also observed in the process $e^+e^- \to \pi^0\pi^0 h_c$ by BESIII [18]. These signals are shown in Fig. 4.

In the process $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$, BESIII also observed a structure $Z_c(4025)^{\pm}$ near $(D^*\bar{D}^*)^{\pm}$ threshold [19]. Similarly, a neutral partner $Z_c(4025)^0$ was observed in the process $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ [20].

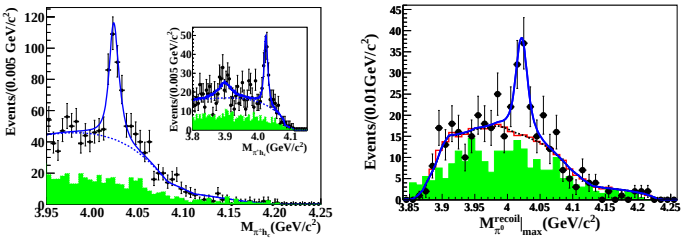

Figure 4: Sum of the simultaneous fits to the $M(\pi^{\pm}h_c)$ (left) and $M(\pi^0 h_c)$ (right) distributions at 4.23, 4.26, and 4.36 GeV in the BESIII data; the inset in the left panel shows the sum of the simultaneous fit to the $M_{\pi^+h_c}$ distributions at 4.23 and 4.26 GeV with $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

4. Measurements of the cross section of e^+e^- →hadron + charmonium

4.1 Measurement of $\sigma(e^+e^- \to \eta^{(\prime)}J/\psi)$

The Born cross section of $e^+e^- \to \eta J/\psi$ was measured at energies 3.81 to 4.6 GeV by BESIII [21][22] as shown in Fig. 5 (left), which are consistent with previous Belle result [23]. The process $e^+e^- \to \eta' J/\psi$ was observed for the first time [24] and the measured Born cross section is shown in Fig. 5 (right) which indicates $\psi(4160) \to \eta' J/\psi$.

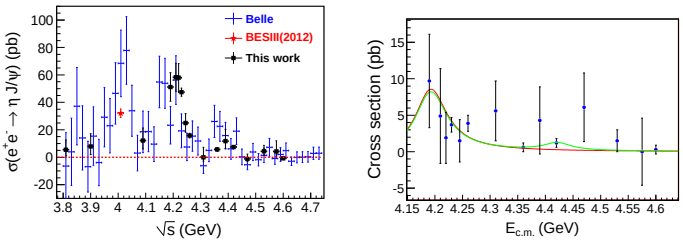

Figure 5: Left: the measured Born cross section of $e^+e^- \to \eta J/\psi$ by BESIII (red star dot and black square dots) and by Belle (blue dots). Right: Fit to the Born cross section of $e^+e \to \eta' J/\psi$ with a $\psi(4160)$ resonance (red curve), or a combination of $\psi(4160)$ and $\psi(4415)$ resonances (green curve). The uncertainties are statistical only.

4.2 Measurement of $\sigma(e^+e^- \to \omega\chi_{cJ})$

BESIII also observed for the first time the processes $e^+e^- \to \omega\chi_{cJ}$ $(J = 0,1,2)$ [25][26], and the measured Born cross sections indicate $\Upsilon(4260) \to \omega\chi_{c0}$ and $\psi(4415) \to \omega\chi_{c2}$.

5. Summary

Using the unique e^+e^- data samples at energies between 3.8 and 4.6 GeV, BESIII contributed significantly on the study of the XYZ states. BESIII will continue these studies and will take more data in the energy region.

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