Charmonium and exotics from Belle

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The recent results on charmonium and charmonium-like states from Belle experiment are reviewed. We summarise searches in $B$ decays for possible $X$-like states in final states containing $\eta_c$. The new measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ improves the determination of the properties of $Y(4360)$ and $Y(4660)$. The fits including $Y(4260)$ are performed. Evidence for a charged charmonium-like structure at 4.05 GeV/$c^2$ is observed in the $\pi^+\psi(2S)$ intermediate state in the $Y(4360)$ decays. Belle also updates the measurement on $e^+e^- \rightarrow K^+K^-J/\psi$ via initial state radiation using the full data sample. Finally, Belle observed $X(3872)$ in $B \rightarrow K\pi + X(\rightarrow \pi^+\pi^-J/\psi)$.

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1 Introduction

In the past decade, many structures above open charm threshold were discovered and most have very exotic properties [1]. Similarly, comparable states with the $b$-quark, such as $Y_b$, and the $s$-quark—the $Y(2175)$—were observed.

The discoveries of the tetra-quark states, $Z_b^+(10610)$ and $Z_b^+(10650)$ [2], with quark content $\bar{u}d\bar{b}b$, and $Z_c^{+}(3900)$ [3] and $Z_c^{+}(4020)$ [4], with quark content $\bar{u}d\bar{c}c$, extend our knowledge about hadrons and QCD: there are not only quark-antiquark mesons or three-quark baryons. It’s very possible that the only requirement on a state is zero net color. In this case, there should be states with five, six or even more quarks.

The Belle experiment ran from 1999 to 2010. In this decade, the world record on luminosity of $L = 2.1 \times 10^{34}$ was achieved. The data taken by Belle experiment are 121 fb$^{-1}$ on $\Upsilon(5S)$, 711 fb$^{-1}$ on the $\Upsilon(4S)$ resonance, 3 fb$^{-1}$ on $\Upsilon(3S)$, 25 fb$^{-1}$ on $\Upsilon(2S)$ and 6 fb$^{-1}$ on $\Upsilon(1S)$. In addition, to study the continuum productions, about 100 fb$^{-1}$ data were recorded off resonance. The full data sample of the Belle experiment is 1 ab$^{-1}$. The huge data sample enhances Belle’s ability to study many processes and states, many of them very rare and statistically limited. Among these are the charmonium and exotic states. Recently, Belle performed studies on 1) $X$-like states decaying to $\eta_c$ modes; 2) an update on $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ via initial state radiation (ISR); 3) an update on $e^+e^- \rightarrow K^+K^-J/\psi$ via ISR; and 4) $X(3872)$ in $B \rightarrow K\pi + J/\psi$.

2 $X$-like states decaying to $\eta_c$ modes

The $X(3872)$ was observed by Belle in $B \rightarrow K(J/\psi\pi^+\pi^-)$ [5] and is a very narrow resonant state with a mass of $M = 3871.69 \pm 0.17$ MeV/$c^2$ and a width of $\Gamma < 1.2$ MeV at 90% Conference Level (C.L.) [6]. The quantum numbers $J^{PC} = 1^{++}$, favored by Belle, were determined conclusively by LHCb from an angular analysis [7]. The nature of the $X(3872)$ remains unclear. One explanation is that $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule; if so, other “$X$-like” particles should exist.

Assuming a pair of $D^0$ or $D^{*0}$ can form a $X$-like particle, the possible particles are listed in Table 1. Belle searched for these possible “$X$-like” particles in $B^\pm \rightarrow K^\pm X$ decays with $X$ decaying to final states containing a $\eta_c$. In the analysis, the test mode $B^\pm \rightarrow K^\pm \psi(2S)(\rightarrow J/\psi\pi^+\pi^-)$ was studied first, and the results are quite consistent with world-average values [6].

No signal was observed in the final states, however. The same final states without an $X$-like state were also studied. The upper limits of BR($B^\pm \rightarrow K^\pm + \eta_c h$) were determined at 90% C.L.; here, $h$ stands for $\pi^+\pi^-$, $\omega$, $\eta$ or $\pi^0$.

Since $Z_c^{\pm}(3900)$ was observed in $\pi^\pm J/\psi$ final states [3] and $Z_c^{\pm}(4020)$ was observed
Table 1: The possible X-like states and their properties.

| Candidate | Combination | Quantum number $J^{PC}$ | Decay modes |
|-----------|-------------|-------------------------|-------------|
| $X_1(3872)$ | $D^0 D^{*0} - D^{*0} D^0$ | $1^{-+}$ | $\eta_c \omega$, $\eta_c \rho$ |
| $X(3730)$ | $D^0 D^* + D^* D^0$ | $0^{++}$ | $\eta_c \eta_c$, $\eta_c \pi^0$ |
| $X(4014)$ | $D^{*0} D^{*0} + D^{*0} D^{*0}$ | $0^{++}$ | $\eta_c \eta_c$, $\eta_c \pi^0$ |

in $\pi^\pm h_c$ final states [4], they may have neutral partners analogous to the observed $Z_c^0(10610)$ and $Z_b^0(10650)$. They may decay to final states containing an $\eta_c$ meson. Additionally, this search is sensitive to the $X(3915)$ that was discovered in $\gamma \gamma$ collisions [8]. Belle doesn’t observe signal in the final states, as shown in Fig. 1.

Figure 1: The distributions of $M_{\eta_c \eta}$ and $M_{\eta_c \pi^0}$ in the decays of $B^\pm \rightarrow K^\pm + X$ at Belle. The curves show the fits with a possible $Z_c^0(3900)$.

3 Update on $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ via ISR

$Y(4360)$ was confirmed and $Y(4660)$ was discovered in the Belle measurement of $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ via ISR [9]. $Y(4660)$ has been confirmed recently by BaBar [10]. $Y(4660)$ is the highest-mass charmoniumlike state; oddly, its width is only $(48 \pm 15 \pm 9)$ MeV, according to Belle’s previous measurement [9]. Additionally, the structure $X(4630)$ observed in $e^+e^-\rightarrow \Lambda_c \Lambda_c$ [11] has a mass close to that of $Y(4660)$; it remains unclear whether they are the same resonance. With an improved reconstruction efficiency, Belle’s full data set yields additional sensitivity to this question in its to update the measurement of $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$. Meanwhile, the $Z_c^+(3900)$ observed in $Y(4260)$ decays is a good candidate of tetra-quark state [3]. Since $Y(4360)$ and $Y(4660)$ share some similar properties with $Y(4260)$, it is important to search for this pattern of possible intermediate state(s) in $Y(4360)$ or $Y(4660)$ decays.

Belle uses the full data sample to update the measurement on $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ [12]. $\psi(2S)\rightarrow \pi^+\pi^- J/\psi$ ($\pi^+\pi^- J/\psi$ mode) and $\psi(2S)\rightarrow \mu^+\mu^-$ ($\mu^+\mu^-$ mode) are used to
reconstruct the $\psi(2S)$ signal. Belle sees 245 candidate events with a purity of 96% from the $\pi^+\pi^- J/\psi$ mode and 118 events with a purity of 60% from the $\mu^+\mu^-$ mode. Figure 2 shows the scatter plots of $M_{\pi^+\pi^-\psi(2S)}$ vs. $M_{\pi^+\pi^-}$. Unbinned simultaneous maximum likelihood fit are performed to $M_{\pi^+\pi^-\psi(2S)}$ for $Y(4360)$ and $Y(4660)$ using $Amp = BW_1 + e^{i\phi} \cdot BW_2$. The fit results are shown in Fig. 3 and Table 2. They are consistent with the previous measurement [9]. No obvious signal is seen above $Y(4660)$ but some events accumulate at $Y(4260)$, especially in the $\pi^+\pi^- J/\psi$ mode.

Figure 2: Invariant mass of the $\pi^+\pi^-$ recoiling against the $\psi(2S)$ versus the invariant mass of the $\pi^+\pi^-\psi(2S)$ in the $\pi^+\pi^- J/\psi$ mode (a) and $\mu^+\mu^-$ mode (b). The horizontal dashed lines show the belt of $f_0(980)$, while the vertical solid lines demarcate the regions with the $Y(4360)$ and $Y(4660)$ states and the higher-mass combinations.

Figure 3: The $\pi^+\pi^-\psi(2S)$ invariant-mass distributions and the simultaneous fit results. From left to right: (a) the $\pi^+\pi^- J/\psi$ mode, (b) the $\mu^+\mu^-$ mode, and (c) the sum.

Since there are events in the vicinity of the $Y(4260)$ mass, an alternative fit with a coherent sum of $Y(4260)$, $Y(4360)$, and $Y(4660)$ amplitudes is performed. The fit results are shown in Fig. 4 and Table 3. The signal significance of the $Y(4260)$ is only $2.4\sigma$ but it affects the masses and widths of $Y(4360)$ and $Y(4660)$.

Belle searches for charged charmoniumlike structures in both $\psi(2S)$ decay modes of the $\pi^\pm\psi(2S)$ system from $Y(4360)$ or $Y(4660)$ decays. In $Y(4360)$ decays, there
Table 2: Results of the fits to the $\pi^+\pi^-\psi(2S)$ invariant-mass spectra. The first error is statistical and the second is systematic. $M$, $\Gamma$, and $\text{BR} \cdot \Gamma_{e^+e^-}$ are the mass (in MeV/$c^2$), total width (in MeV), and the product of the branching fraction to $\pi^+\pi^-\psi(2S)$ and the $e^+e^-$ partial width (in eV), respectively; $\phi$ is the relative phase between the two resonances (in degrees).

| Parameters | Solution I | Solution II |
|------------|------------|-------------|
| $M_{Y(4360)}$ | 4347 ± 6 ± 3 | 103 ± 9 ± 5 |
| $\Gamma_{Y(4360)}$ | $9.2 \pm 0.6 \pm 0.6$ | $10.9 \pm 0.6 \pm 0.7$ |
| $BR[Y(4360) \rightarrow \pi^+\pi^-\psi(2S)] \cdot \Gamma_{e^+e^-}$ | $4652 \pm 10 \pm 11$ | $68 \pm 11 \pm 5$ |
| $M_{Y(4660)}$ | $2.0 \pm 0.3 \pm 0.2$ | $8.1 \pm 1.1 \pm 1.0$ |
| $\Gamma_{Y(4660)}$ | $32 \pm 18 \pm 20$ | $272 \pm 8 \pm 7$ |

Table 3: Results of the alternative fits to the $\pi^+\pi^-\psi(2S)$ invariant-mass spectra using three resonances: $Y(4260)$, $Y(4360)$, and $Y(4660)$. The parameters are the same as in Table 2 except that, here, $\phi_1$ is the relative phase between the $Y(4360)$ and $Y(4260)$ (in degrees) and $\phi_2$ is the relative phase between the $Y(4360)$ and $Y(4660)$ (in degrees).

| Parameters | Solution III | Solution IV | Solution V | Solution VI |
|------------|--------------|-------------|------------|-------------|
| $M_{Y(4260)}$ | 4259 (fixed) | 134 (fixed) | $1.5 \pm 0.6 \pm 0.4$ | $4.1 \pm 1.0 \pm 0.6$ |
| $\Gamma_{Y(4260)}$ | $1.7 \pm 0.7 \pm 0.5$ | $4.9 \pm 1.3 \pm 0.6$ | $10.4 \pm 1.3 \pm 0.8$ | $21.1 \pm 3.5 \pm 1.4$ |
| $BR \cdot \Gamma_{e^+e^-}$ | $4365 \pm 7 \pm 4$ | $4660 \pm 9 \pm 12$ | $8.9 \pm 1.2 \pm 0.8$ | $17.7 \pm 2.6 \pm 1.5$ |
| $M_{Y(4360)}$ | $74 \pm 14 \pm 4$ | $74 \pm 12 \pm 4$ | $10.4 \pm 1.3 \pm 0.8$ | $21.1 \pm 3.5 \pm 1.4$ |
| $\Gamma_{Y(4360)}$ | $2.2 \pm 0.4 \pm 0.2$ | $2.2 \pm 0.4 \pm 0.2$ | $9.3 \pm 1.2 \pm 1.0$ | $17.7 \pm 2.6 \pm 1.5$ |
| $\phi_1$ | $304 \pm 24 \pm 21$ | $304 \pm 24 \pm 21$ | $9.3 \pm 1.2 \pm 1.0$ | $24 \pm 0.5 \pm 0.3$ |
| $\phi_2$ | $26 \pm 19 \pm 10$ | $26 \pm 19 \pm 10$ | $24 \pm 0.5 \pm 0.3$ | $17.7 \pm 2.6 \pm 1.5$ |
Figure 4: The four solutions from the fit to the $\pi^+\pi^-\psi(2S)$ invariant mass spectra with the $Y(4260)$ included. The curves show the best fit and the dashed curves show the contributions from the two Breit-Wigner (BW) components.

is an excess evident at around 4.05 GeV/c$^2$ in the $\pi^+\psi(2S)$ invariant-mass distributions in both $\pi^+\pi^-J/\psi$ and $\mu^+\mu^-$ modes. An unbinned maximum-likelihood fit is performed simultaneously for both modes on the distribution of $M_{\text{max}}(\pi^+\psi(2S))$, the maximum of $M(\pi^+\psi(2S))$ and $M(\pi^-\psi(2S))$. The fit yields a mass of $(4054 \pm 3\,\text{(stat.}) \pm 1\,\text{(syst.)})$ MeV/c$^2$ and a width of $(45 \pm 11\,\text{(stat.}) \pm 6\,\text{(syst.)})$ MeV for the excess, as shown in Fig. 5. The significance of this excess is $3.5\sigma$. No charged structure is found in $Y(4660)$ decays.

4 Update on $e^+e^- \rightarrow K^+K^-J/\psi$ via ISR

The first scan on this channel was performed by Belle [13]. The cross section of $e^+e^- \rightarrow K^+K^-J/\psi$ was measured from threshold to 5.5 GeV/c$^2$. Unlike the final states of $\pi^+\pi^-J/\psi$ and $\pi^+\pi^-\psi(2S)$, in which clear resonant signals were observed, the distribution of $M_{K^+K^-J/\psi}$ lacked evidence for structure.

Recently, Belle has updated this measurement with the full data sample [14]. Despite the enhanced statistics, there is still no $Y$ state observed in the final states. The $M_{K^+K^-J/\psi}$ distribution is shown in Fig. 6. Additionally, Belle searched for $Z_{cs} \rightarrow KJ/\psi$ in this analysis. As shown in Fig. 7, no evident structure in $K^\pm J/\psi$ mass distribution is observed.
Figure 5: The distribution of $M_{\text{max}}(\pi^+\psi(2S))$ from $Y(4360)$-subsample decays. The solid curve is the best fit and the dashed curve is the signal parametrized by a BW function.

Figure 6: Fits to $M_{K^++K^-J/\psi}$ distribution at Belle. The solid curves show the best fit to data and background with one BW function (a) and the coherent sum of a BW function and the $\psi(4415)$ component (b).

5 Study of $B \rightarrow X(3872)K\pi$

The $X(3872)$ was discovered in $B^+ \rightarrow X(3872)(\rightarrow \pi^+\pi^-J/\psi)K^+$ and has a definitive $J^{PC}$ assignment of $1^{++}$ [7]. It has been observed to decay to several other final states: $J/\psi\gamma$, $\psi(2S)\gamma$, $J/\psi\pi^+\pi^-\pi^0$ and $D^0D^{*0}$. Recently, Belle searched for $X(3872)$ in another final state: $B \rightarrow X(3872)(\rightarrow \pi^+\pi^-J/\psi)K\pi$ [15]. Figure 8 shows the signals seen in both $B^+$ and $B^0$ decays. The extracted branching fraction is $\text{BR}(B \rightarrow X(3872)K\pi) \times \text{BR}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$ in $B^0$ decay and $(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$ in $B^+$ decay, which agree with each other quite well. In addition, Belle finds that $B^0 \rightarrow X(3872)K^*(892)^0$ does not dominate the $X(3872)K^+\pi^-$ final state.
Figure 7: The invariant-mass distributions of (a) $K^+K^-$, (b) $K^+J/\psi$ and (c) $K^-J/\psi$.

Figure 8: $X(3872)$ in $B^0 \to X(3872)(\to \pi^+\pi^-J/\psi)K^+\pi^-$ decays (a) and $B^\pm \to X(3872)(\to \pi^+\pi^-J/\psi)K_s\pi^\pm$ (b).

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