

Spectroscopy results from Belle

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We report recent results on the charmonium and charmoniumlike states based on a large data sample recorded at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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1. Introduction

Starting with the observation of the $\eta_c(2S)$ state, a number of new states have been observed by Belle. Some of these have been identified as being the predicted, but not-yet-seen, charmonium states, while others, designated by X , Y & Z , are considered to be candidates for new types of charmoniumlike states such as hybrid $c\bar{c}$ -gluon states or multiquark states either of the molecular type ($c\bar{q}c\bar{q}$) or the diquark-diantiquark ($cq\bar{c}\bar{q}$) type. Here, recent XYZ state-related measurements are reported and examined in the context of possible charmonium assignments.

2. The $X(3872)$

The $X(3872)$ was discovered by Belle in the $J/\psi\pi^+\pi^-$ mass spectrum in exclusive $B \rightarrow KX(3872)$ decay [1] in a 140 fb^{-1} data sample; it was subsequently seen in three other experiments. One curious fact about the $X(3872)$ is the near equality of its mass and the $m_{D^0}+m_{D^{*0}}$ threshold. The latest PDG world averaged mass [2] is $3871.56 \pm 0.22 \text{ MeV}$, while the D^0D^{*0} mass threshold is $3871.79 \pm 0.30 \text{ MeV}$. The CDF group reported that only the J^{PC} options 1^{++} and 2^{-+} are compatible with the J/ψ and $\pi\pi$ helicity angle distributions [3]. It is also now well established that the $\pi\pi$ system in $X \rightarrow J/\psi\pi^+\pi^-$ comes from $\rho \rightarrow \pi\pi$ decays.

2.1 $X(3872) \rightarrow \gamma J/\psi(\psi')$

The observation of $X(3872)$ in $\gamma J/\psi(\psi')$ final states ensures that the charge-conjugation parity of the $X(3872)$ is $C = +1$. The first reported evidence for $X(3872) \rightarrow \gamma J/\psi$ was given by Belle [4] using in $B \rightarrow KX(3872)$ decays in a 256 fb^{-1} data sample with a signal significance of $\sim 4\sigma$.

BaBar also reported $X(3872)$ decays to both $\gamma J/\psi$ and $\gamma\psi'$ final states in the $B^+ \rightarrow K^+\gamma J/\psi(\psi')$ process [5], with signal significances of 3.6σ and 3.5σ , respectively. Their measured product of branching fractions are $B(B^+ \rightarrow K^+X(3872)) \times B(X(3872) \rightarrow \gamma J/\psi) = (2.8 \pm 0.8) \times 10^{-6}$ and $B(B^+ \rightarrow K^+X(3872)) \times B(X(3872) \rightarrow \gamma\psi') = (9.5 \pm 2.8) \times 10^{-6}$. The ratio of these branching fractions is $\frac{B(X_{3872} \rightarrow \gamma\psi')}{B(X_{3872} \rightarrow \gamma J/\psi)} = 3.4 \pm 1.4$, which is large for a $D\bar{D}^{*0}$ molecular state [6]

This year Belle studied the $\gamma J/\psi(\psi')$ final states using their full data sample of $772 \times 10^6 B\bar{B}$ events [7]. The $B \rightarrow K\gamma J/\psi$ channel is dominated by $B \rightarrow K\chi_{c1}$; $\chi_{c1} \rightarrow \gamma J/\psi$ decays and this is used as a calibration reaction; the branching fraction for the well known $B^+ \rightarrow K^+\chi_{c1}$ decay is measured to be $(4.94 \pm 0.35) \times 10^{-4}$, which agrees well with the PDG value [2]. Belle also reported first evidence for $B \rightarrow K\chi_{c2}$ (via $\chi_{c2} \rightarrow \gamma J/\psi$) with 3.6σ significance. The branching fraction for $B^+ \rightarrow K^+\chi_{c2}$ is measured to be $(1.11 \pm 0.37) \times 10^{-5}$. The ratio of branching fractions $\frac{B(B^+ \rightarrow K^+\chi_{c2})}{B(B^+ \rightarrow K^+\chi_{c1})}$ is 0.022 ± 0.007 , which is a measure of the factorization suppression factor for $J^{PC} = 2^{++}$. In the same $\gamma J/\psi$ final state but at higher masses, there is a clear $X(3872) \rightarrow \gamma J/\psi$ signal with 4.9σ significance. Figure 1 shows $M_{\gamma J/\psi}$ mass distributions in exclusive (a) $B^+ \rightarrow K^+\gamma J/\psi$ and (b) $B^0 \rightarrow K_S^0\gamma J/\psi$ decay. The product of branching fractions for $B \rightarrow KX$ and $X \rightarrow \gamma J/\psi$ is measured to be $(1.8 \pm 0.5) \times 10^{-6}$, which agrees with the BaBar result. However, there is no significant signal for $B^+ \rightarrow K^+X$ and $X \rightarrow \gamma\psi'$ decay. Figures 1 show the $M_{\gamma\psi'}$ mass distributions in $B^+ \rightarrow K^+\gamma\psi'$ decay for (c) $\psi' \rightarrow \ell^+\ell^-$ and (d) $\psi' \rightarrow J/\psi\pi^+\pi^-$ decays. An upper limit of the product of branching fractions is determined to be $B(B^+ \rightarrow K^+X) \times (X \rightarrow \gamma\psi') < 3.4 \times 10^{-6}$. The

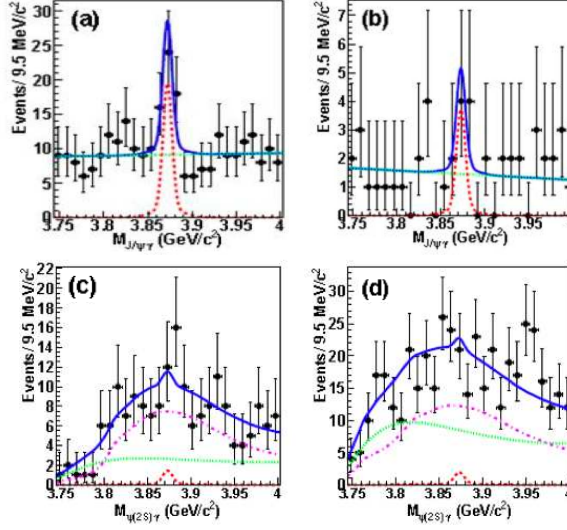


Figure 1: $\gamma J/\psi$ mass distributions (top) for (a) $B^+ \rightarrow K^+ X(3872)$ and (b) $B^0 \rightarrow K_s^0 X(3872)$ candidate events with subsequent $X(3872) \rightarrow \gamma J/\psi$ decay. $\gamma \psi'$ mass distributions (bottom) for $B^+ \rightarrow K^+ X(3872)$ candidate events with subsequent $X(3872) \rightarrow \gamma \psi'$ decay, where $\psi' \rightarrow \ell^+ \ell^-$ in (c) and $\pi^+ \pi^- J/\psi$ in (d).

ratio of branching fractions of its 90% CL upper limit is $\frac{B(X \rightarrow \gamma \psi')}{B(X \rightarrow \gamma J/\psi)} < 2.1$, in contradiction with the BaBar result.

2.2 $X(3872) \rightarrow \omega J/\psi$

In the $D^0 \bar{D}^{*0}$ molecular model of Swanson [6], the J^{PC} is assumed to be 1^{++} , in which case the $D^0 \bar{D}^{*0}$ component is dominant, with small admixtures of $\omega J/\psi$ and $\rho J/\psi$. In this model, $X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi$ decays were predicted to occur at about half the rate for $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ decay. Belle performed a search for this $3\pi J/\psi$ decay mode.

Figure 2(b) shows the $Y(3940)$ [8] seen in $\omega J/\psi$ mass distribution in $B \rightarrow K \omega J/\psi$ decay. In the $X(3872)$ mass region, which is at the right edge of the kinematic boundary, Belle observes a signal in the 3π mass spectrum corresponding to the sub-threshold decay $X(3872) \rightarrow \omega J/\psi$. The measured number of signal events were 12.4 ± 4.1 , from which the ratio of the branching fractions $\frac{B(X_{3872} \rightarrow \omega J/\psi)}{B(X_{3872} \rightarrow \pi^+ \pi^- J/\psi)}$ is determined to be 1.0 ± 0.5 [4].

This year BaBar reanalyzed $B \rightarrow K \omega J/\psi$ final states using a relaxed omega mass selection [9] $0.5 < m_{3\pi} < 0.9$ GeV and saw a similar ω signal. Using their reported branching fraction, we obtain the combined ratio from Belle and BaBar to be $\frac{B(X_{3872} \rightarrow \omega J/\psi)}{B(X_{3872} \rightarrow \pi^+ \pi^- J/\psi)} = 0.8 \pm 0.3$. In addition, BaBar reports that the $M_{3\pi}$ mass spectrum from the $X_{3872} \rightarrow J/\psi \omega$ final states is suppressed near its upper kinematic boundary by a centrifugal barrier factor that is consistent with a P -wave. Their P -wave (2^-) fit ($\chi^2/\text{NDF} = 3.53/5$) to the $M_{3\pi}$ mass distribution is favored over their S -wave (1^+) fit ($\chi^2/\text{NDF} = 10.17/5$). This would be bad for a molecular interpretation of $X(3872)$, however, this corresponds to only about a 1.5σ effect.

2.3 Charmonium possibilities of $X(3872)$

From the CDF angular analysis results [3], the only two possible J^{PC} assignments for the X

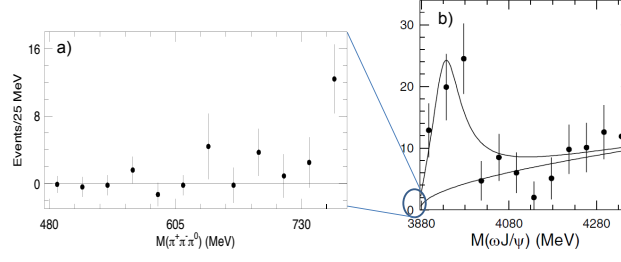


Figure 2: a) The B-meson signal yields versus 3π invariant mass in the $X(3872)$ region of $M_X - 3\sigma < M_X < M_X + 1\sigma$ for $B \rightarrow K\pi^+\pi^-\pi^0 J/\psi$ decay. b) $B \rightarrow K\omega J/\psi$ signal yields versus $M(\omega J/\psi)$

are 1^{++} and 2^{-+} ; all other J^{PC} values are ruled out with high confidence. In this section, we survey charmonium possibilities for $X(3872)$ with these two J^{PC} assignments.

For the 1^{++} assignment, the possible undiscovered charmonium state is χ'_{c1} . For the $X(3872) = \chi'_{c1}$ assignment, the following puzzling questions arise.

- Since the mass of χ'_{c2} is now known to be 3930 MeV [10], the mass of χ'_{c1} is expected to be ~ 3905 MeV. Therefore, the mass of $X(3872)$ is too low for it to be the χ'_{c1} .
- Barnes *et al.* [11] estimated the partial width for $\Gamma(\chi_{c1}' \rightarrow \gamma\psi') \sim 180$ keV, while $\Gamma(\chi_{c1}' \rightarrow \gamma J/\psi) \sim 14$ keV. So, the ratio of partial widths $\frac{\Gamma(\chi_{c1}' \rightarrow \gamma\psi')}{\Gamma(\chi_{c1}' \rightarrow \gamma J/\psi)}$ should be much bigger than unity. Therefore, the χ_{c1}' assignment would be a possible option if the BaBar measurement is right, which gives a large partial width for the $\gamma\psi'$ mode.
- $\Gamma(X \rightarrow \pi^+\pi^- J/\psi) = (3.4 \pm 1.2) \times \Gamma(X \rightarrow \gamma J/\psi)$ is estimated to be about 45 keV using the Barnes value for $\Gamma_{\gamma J/\psi}$ and the measured ratio of $\frac{\Gamma_{\pi\pi J/\psi}}{\Gamma_{\gamma J/\psi}}$. This partial width for $X \rightarrow \pi^+\pi^- J/\psi$ decay is huge for an isospin-violating transition; other isospin violating transitions in the charmonium system are less than 1 keV (*e.g.*, $\Gamma(\psi' \rightarrow \pi^0 J/\psi) \sim 0.4$ keV [2]).

For the 2^{-+} assignment, the possible undiscovered charmonium state is the singlet D -wave state known as the $\eta_{c2}(^1D_2)$. For this assignment, the following questions arise.

- Y. Jia *et al.* [12] estimated the partial widths to be $\Gamma(\eta_{c2} \rightarrow \gamma\psi') \sim 0.4$ keV and $\Gamma(\eta_{c2} \rightarrow \gamma J/\psi) \sim 9$ keV. This favors the Belle measurement where the ratio $\frac{\Gamma(\eta_{c2} \rightarrow \gamma\psi')}{\Gamma(\eta_{c2} \rightarrow \gamma J/\psi)}$ is smaller.
- Using the well established mass of its multiplet partner, $M(\psi'') = 3770$ MeV, the mass of the η_{c2} is estimated to be 3837 MeV. Thus, the $X(3872)$ mass is high for η_{c2} .
- $\Gamma(X \rightarrow \pi^+\pi^- J/\psi) = (3.4 \pm 1.2)(X \rightarrow \gamma J/\psi)$ is about 30 keV using the Jia $\gamma J/\psi$ width. This is also large for an isospin-violating transition.
- For the $2^{-+}(\eta_{c2})$ assignment, the branching fraction for the $B^+ \rightarrow K^+\eta_{c2}$ is too high for a non-factorizable decay. Other two $B^+ \rightarrow K^+h_c$ and $B^+ \rightarrow K^+\chi_{c2}$ decay, which is also non-factorizable and suppressed by an angular momentum barrier, are just barely seen in the huge Belle data sample.
- The branching fraction for $\eta_{c2} \rightarrow D\bar{D}^*$ is expected to be small [13], but the averaged ratio from both Belle and BaBar is $\frac{\Gamma(X \rightarrow D\bar{D}^*)}{\Gamma(X \rightarrow \pi\pi J/\psi)} = 9.5 \pm 3.1$, which is high for the η_{c2} .

3. More X and Y states near 3940 MeV

Belle observed three states near 3940 MeV via three different production and decay channels [8, 10, 14]. Among these three, the $Z(3930)$ state, which is produced in the $\gamma\gamma \rightarrow D\bar{D}$ process, is generally considered to be the charmonium χ'_{c2} state, even though the mass $M=3929 \pm 5 \pm 2$ MeV is somewhat lower than potential model predictions. The $X(3940)$ is observed in the $D\bar{D}^*$ mass spectrum from double charmonium production in $e^+e^- \rightarrow J/\psi D^*\bar{D}$ annihilation and the $Y(3940)$ is observed in the $\omega J/\psi$ mass spectrum in $B \rightarrow K\omega J/\psi$ decays. The mass and width of the $X(3940)$ ($Y(3940)$) are measured to be $M=3942^{+7}_{-6} \pm 6$ ($3943 \pm 11 \pm 13$) MeV and $\Gamma = 37^{+26}_{-15} \pm 8$ ($87 \pm 22 \pm 26$) MeV. Although the masses are similar, the $X(3940)$ and $Y(3940)$ appear to be different states: the $X(3940)$ ($Y(3940)$) has not been seen in the $\omega J/\psi$ ($D\bar{D}^*$) final state in $B \rightarrow X(Y)K$ decays.

It is important to search for $\omega J/\psi$ (or $D\bar{D}^*$) in two-photon collisions, where its spin-parity of resonance is preferentially constrained to be $J^P=0^\pm$ or 2^\pm . Belle observed a 7.7σ enhancement in the $\omega J/\psi$ system [15] produced in the $\gamma\gamma \rightarrow \omega J/\psi$ process; the mass and total width are measured to be $M=3915 \pm 3 \pm 2$ MeV and $\Gamma=17 \pm 10 \pm 3$ MeV. This state, denoted by $X(3915)$, is probably related to one of the three above-mentioned states in the 3.90-3.95 GeV mass region. If we assume the $X(3915)$ is 0^+ (2^+) resonance, the product of the two-photon decay width and branching fraction to $\omega J/\psi$ is determined to be $\Gamma_{\gamma\gamma}(X(3915))B(X \rightarrow \omega J/\psi) = 61 \pm 17 \pm 8(18 \pm 5 \pm 2)$ eV for $J^P = 0^+$ (2^+). For comparison, the measured product of the two-photon decay width and branching fraction for $Z(3930) \rightarrow D\bar{D}$ is $180 \pm 50 \pm 30$ eV. If the $X(3915)$ is the $Z(3930)$ (χ'_{c2}), the ratio of branching fractions $\frac{BF(\chi'_{c2} \rightarrow \omega J/\psi)}{BF(\chi'_{c2} \rightarrow D\bar{D})}$ is large for an above-open-charm-threshold charmonium state. Also, for both the 0^+ and 2^+ options, if we assume that the $\gamma\gamma$ partial width is ~ 1 keV, which is typical for charmonium states, $\Gamma_{\omega J/\psi}$ would be of the order of 1 MeV, which is large for charmonium.

The $\Gamma(Y_{3940} \rightarrow \omega J/\psi)$ partial width is also estimated to be large using the averaged product branching fraction from Belle and BaBar to be $B(B^+ \rightarrow K^+ Y_{3940}) \times B(Y_{3940} \rightarrow \omega J/\psi) = (5.0 \pm 0.8) \times 10^{-5}$ and the PDG averaged $\Gamma(Y_{3940}) = 40^{+18}_{-13}$ MeV. If we assume the maximum possible branching fraction for $B \rightarrow KY_{3940}$ is 10×10^{-4} (the branching fraction for $B \rightarrow KJ/\psi$), the partial width for $\Gamma(Y_{3940} \rightarrow \omega J/\psi)$ is determined to be larger than order 1 MeV, which is large for conventional charmonium.

4. The $Y(4260)$ and Y_b

The 1^{--} $Y(4260)$ state was first discovered by BaBar [16] and confirmed by Belle [17] in the $J/\psi\pi^+\pi^-$ in radiative $e^+e^- \rightarrow \gamma_{SR}Y(4260)$ process. The partial width for $Y \rightarrow \pi^+\pi^-J/\psi$ is determined to be larger than 0.5 MeV at the 90% CL level by Mo *et al.* [18], which is much larger than that for $\psi' \rightarrow \pi^+\pi^-J/\psi$. This large partial width is one of the remarkable properties of the $Y(4260)$ that have led to various exotic interpretations of its quark content. An interesting question is whether or not there exist counterparts in the $s\bar{s}$ and/or $b\bar{b}$ quark systems.

Belle reported an anomalously large $e^+e^- \rightarrow Y(1,2S)\pi^+\pi^-$ production cross section near the peak of the $Y(5S)$ resonance at $\sqrt{s} \sim 10.87$ GeV measured with a 21.7fb^{-1} data sample [19]. If they assume that the signal events only come from decays of the $Y(5S)$ resonance, their extracted partial

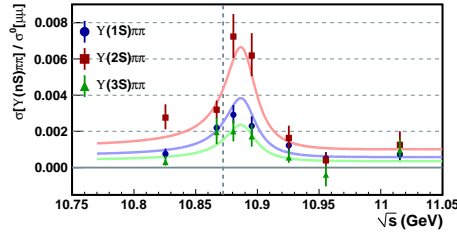


Figure 3: The $\Upsilon(nS)\pi\pi$ ($n=1,2$ and 3) cross sections near the $\Upsilon(5S)$ resonance show peak structure that deviates from the peak (vertical line) of $\Upsilon(5S)$ obtained from the hadronic cross sections.

widths are ~ 300 times larger than those for corresponding transitions from the $\Upsilon(4S)$. Recently, Belle measured the energy dependence of the $e^+e^- \rightarrow \Upsilon(nS)\pi\pi$ ($n=1,2,3$) production cross section using data accumulated at seven different cm energy points near the $\Upsilon(5S)$ resonance. A new common peak structure was observed for all three $e^+e^- \rightarrow \Upsilon(1,2,3S)\pi^+\pi^-$ cross sections. A fit using Breit-Wigner resonance function with a common mass and width to these peaks, shown in Fig. 3, gives a mass and width of $M=10888.4^{+2.7}_{-2.6} \pm 1.2$ MeV and $\Gamma = 30.7^{+8.3}_{-7.0} \pm 3.1$ MeV[20], which are not consistent with any known $b\bar{b}$ state such as the $\Upsilon(10860)$. This can be considered to be a candidate for a Y_b -type state in the $b\bar{b}$ system.

5. Charged Z^+ states

A charged charmonium-like state could not be a $c\bar{c}$ charmonium state; its minimal quark structure would have to be a $c\bar{c}u\bar{d}$ tetraquark arrangement. The charged $Z(4430)^+$ state was first observed by Belle as a peak in the $\pi^+\psi'$ mass distribution in exclusive $B \rightarrow K\pi^+\psi'$ decays[21]. It was confirmed by a subsequent reanalysis using a Dalitz plot formalism [22] that includes all possible intermediate $K\pi$ resonances. This Dalitz analysis method was first employed in the observation of two other charged Z_1^+ and Z_2^+ states that are seen to decay to $\pi^+\chi_{c1}$ final states in exclusive $B \rightarrow K\pi^+\chi_{c1}$ decays [23]. The Dalitz-plot analysis demonstrated that these Z states are not produced by reflections from any known and possibly unknown resonances in the $K\pi$ channel. However, BaBar searched for the $Z(4430)^+$, but did not see a significant signal [24].

Acknowledgments

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