XYZ particles at Belle*

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Abstract In this paper, I review recent progress in the study of the XYZ particles at Belle. I only focus on studies with charmonium and one or more light mesons in the final states. This covers the X(3872), X(3915), Y(4140), X(4350), and the charged Z states.

Key words X(3872), X(3915), Y(4140), X(4350), charged Z

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1 Introduction

Recent experimental observations near the charm threshold strongly suggest that the spectrum of resonances with hidden charm is remarkably more rich than suggested by the standard quark-antiquark template and very likely includes states where the heavy-quark $c\bar{c}$ pair is accompanied by light quarks and/or gluons. Lots of new charmonium-like resonances (XYZ particles) in the B factories have been observed in the final states with a charmonium and some light hadrons. They could be candidates for usual charmonium states, however, there are also lots of strange properties shown from these states.

The following XYZ particles, that I will consider in this paper, are the X(3872), X(3915), Y(4140), X(4350), and the charged Z states. The X(3915) and X(4350) found in two-photon processes, and the Y(4140) found in B decays are new observations. The results of searching for possible X/Y states in the $\Upsilon(1S)$ radiative decays are also reported here for the first time.

2 The X (3872)

The X(3872) was discovered by Belle in 2003 [1] as a narrow peak in the $\pi^+\pi^-J/\psi$ invariant mass distribution from $B \rightarrow K\pi^+\pi^-J/\psi$ decays. This discovery mode was remeasured with more statistics at Belle. Belle reported a new result for the mass of the X(3872) as $M^{\rm Belle}_{\rm X(3872)} = 3871.46\pm0.37\pm 0.07$ MeV [2]. The most precise measurement of the mass was reported by CDF using the same decay channel: $M^{\rm CDF}_{\rm X(3872)} = 3871.61\pm0.16\pm0.19$ MeV [3]. A new world average that includes these new measurements plus other results that use the $\pi^+\pi^-J/\psi$ decay mode is $M^{\rm avg}_{\rm X(3872)} = 3871.46\pm0.19$ MeV, which is very close to the $D^{*0}\bar{D}^0$ mass threshold: $m_{D^{*0}} + m_{D^0} = 3871.81\pm0.36$ MeV [4]. This suggests a binding energy of -0.35 ± 0.41 MeV if X(3872) is interpreted as a $D^{*0}\bar{D}^0$ molecule. Belle also reported the first statistically significant observation of $B^0 \rightarrow X(3872)K^0_S$ and measured the ratio of branching fractions to be

$$\frac{\mathcal{B}(B^0\rightarrow X(3872)K^0)}{\mathcal{B}(B^+\rightarrow X(3872)K^+)} = 0.82\pm0.22\pm0.05,$$

consistent with unity. The mass difference between the X(3872) states produced in B^+ and B^0 decay is found to be $M_X^{B^+} - M_X^{B^0} = 0.18\pm0.89\pm0.26$ MeV, consistent with zero.

In addition, Belle did a study of X(3872) production in association with a $K\pi$ in $B^0\rightarrow K^+\pi^-\pi^+\pi^-J/\psi$ decays [2]. In a sample of 657M $B\bar{B}$ pairs a signal of about 90 $X(3872)\rightarrow\pi^+\pi^-J/\psi$ events was observed. Unlike the $B^0\rightarrow K^+\pi^-$+charmonium where $K^+\pi^-$ is mainly from $K^*(892)$ decays, it is evident that most of the $K\pi$ pairs have a phase space-like distribution, with little or no signal for $K^*(892) \rightarrow K\pi$. Belle measures $\mathcal{B}(B^0 \rightarrow X(3872)(K^+\pi^-)_{\rm NR})\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) = (8.1\pm2.0^{+1.1}_{-1.4})\times10^{-6}$ and sets the 90% C.L. limit, $\mathcal{B}(B^0 \rightarrow X(3872)K^*(892))\mathcal{B}(X(3872) \rightarrow$

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$\pi^+\pi^- J/\psi) < 3.4\times10^{-6}$. Belle reports a $K^*(892)$ to $K\pi$ non-resonant ratio of

$$\frac{\mathcal{B}(B\to(K^+\pi^-)_{K^*(892)}J/\psi)}{\mathcal{B}(B\to(K^+\pi^-)_{NR}J/\psi)}<0.55,$$

at the 90% C.L. [5]. This is an indication that the X(3872) state is not a conventional charmonium state. However, there is no solid calculation of the above ratio assuming different nature for the X(3872) state.

BABAR studied $B\to KD^{*0}\bar{D}^0$ with a sample of 383M $B\bar{B}$ pairs and found a similar near-threshold enhancement that, if considered to be due to the $X(3872)\to D^{*0}\bar{D}^0$, gave a mass of $3875.1^{+0.7}_{-0.5}\pm0.5$ MeV [6]. This state has been considered to be a state different from the X(3872) in the literature. However, a subsequent Belle study of $B\to KD^{*0}\bar{D}^0$ based on 657M $B\bar{B}$ pairs was performed for both $D^{*0}\to D^0\gamma$ and $D^{*0}\to D^0\pi^0$ decay modes. Belle found a signal of $50.1^{+14.8}_{-11.1}$ events with a mass of $3872.9^{+0.6+0.4}_{-0.4-0.5}$ MeV, a width of $3.9^{+2.8+0.2}_{-1.4-1.1}$ MeV by fitting the peak on the $D^{*0}\bar{D}^0$ invariant mass distribution with a phase-space modulated Breit-Wigner (BW) function [7]. The branching fraction of $\mathcal{B}(B\to X(3872)K)\mathcal{B}(X(3872)\to D^{*0}\bar{D}^0)$ was measured to be $(0.80\pm0.20\pm0.10)\times10^{-4}$. The significance of the signal is 6.4σ. The difference between the X(3872) mass and the $D^{*0}\bar{D}^0$ threshold is calculated to be $1.1^{+0.6+0.1}_{-0.4-0.3}$ MeV.

3 The X(3915)

Three new (neutral) states have been discovered by Belle in the 3.90–3.95 GeV region. The X(3940) has been found in the double charmonium production process, and its sizable decay to $D^*\bar{D}$ is confirmed [8]. The Y(3940) has been observed in the B decay process $B^-\to Y(3940)K^-$ and $Y(3940)\to\omega J/\psi$ [9], and is a candidate for an exotic state, such as a hybrid meson ($c\bar{c}g$). The Z(3930) has been found as a $D\bar{D}$ mass peak in $\gamma\gamma\to D\bar{D}$ events [10], and is usually assigned to a 2^3P_2 $c\bar{c}$ charmonium state, which is commonly called the χ'_{c2}. These three states appear in different production and decay processes, and are usually considered to be distinct particles. However there is no decisive evidence for this. Predictions of partial decay widths of Y(3940) to $\gamma\gamma$ and $\omega J/\psi$ states was calculated based on an interpretation of Y(3940) as a $D^*\bar{D}^*$ bound state [11].

To add more information on the states in this mass region, it is important to search for a signature of Y(3940) or any other resonant state decaying to $\omega J/\psi$ in two-photon processes. This final state is the lightest combination of two vector mesons with definite C-even and $I=0$ quantum numbers that can be produced in two-photon processes via a hidden-charm state. This analysis is based on a 694 fb^{-1} data sample collected at the $\Upsilon(nS)$ ($n=3,4,5$) resonances and 60 MeV below the $\Upsilon(4S)$ resonance.

Belle observed a dramatic and rather narrow peak around 3.92 GeV, X(3915), in the cross section for $\gamma\gamma\to\omega J/\psi$ [12]. The invariant mass distribution for the $\omega J/\psi$ candidates produced in $\gamma\gamma$ collision, shown in Fig. 1, shows a sharp peak near threshold and not much else. It is far above the non-$\omega J/\psi$ background contribution which is estimated by the events in the ω and J/ψ mass sidebands (shown shaded for comparison). An unbinned maximum likelihood fit was performed to the 73 events in the region from 3.875 GeV to 4.2 GeV.

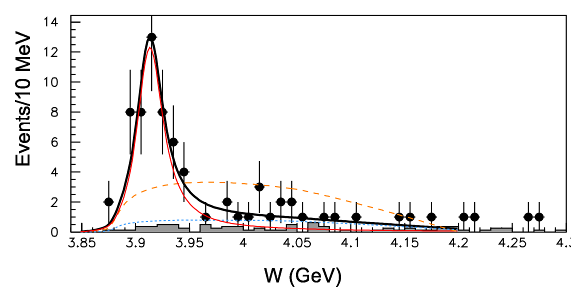

Fig. 1. The $\omega J/\psi$ mass distribution for selected events in the $\gamma\gamma\to\omega J/\psi$ process. The dots with error bars are the experimental data. The shaded histogram is the distribution of non-$\omega J/\psi$ backgrounds estimated by the sideband distributions. The bold solid, thinner solid and the lower dashed curves are the total, resonance and background contributions, respectively, from the fit. The upper dot-dashed curve is the fit without assuming a resonance.

A fit with an S-wave BW function with a variable width for the resonance component plus a smooth background function gives results for the resonance parameters of the X(3915): $M=(3915\pm3\pm2)$ MeV, $\Gamma=(17\pm10\pm3)$ MeV. The statistical significance of the signal is 7.7σ. This value for the mass is about 2σ different from that of the Z(3930) ($M=3929\pm5\pm2$ MeV), indicating that these two peaks may not be different decay channels of the same state. On the other hand, there is good agreement between these preliminary results and the mass and width quoted by BABAR for the Y(3940), which is also seen in $\omega J/\psi$.

The product of the X(3915) two-photon decay width and the branching fraction to $\omega J/\psi$ depends on the J^P value. Belle determines

$$\Gamma_{\gamma\gamma}(\mathrm{X}(3915))\mathcal{B}(\mathrm{X}(3915)\to\omega\mathrm{J}/\psi)=61\pm17\pm8\ \mathrm{eV},$$

or

$$\Gamma_{\gamma\gamma}(\mathrm{X}(3915))\mathcal{B}(\mathrm{X}(3915)\to\omega\mathrm{J}/\psi)=18\pm5\pm2\ \mathrm{eV},$$

for $J^P=0^+$ or 2^+, respectively.

Based on this result, and the measured width Γ, the product of the two partial widths of the X(3915), $\Gamma_{\gamma\gamma}(\mathrm{X})\Gamma_{\omega\mathrm{J}/\psi}(\mathrm{X})$ is of order 10^3 keV^2. If we assume $\Gamma_{\gamma\gamma}\sim\mathcal{O}$ (1 keV), typical for an excited charmonium state, this implies $\Gamma_{\omega\mathrm{J}/\psi}\sim\mathcal{O}$ (1 MeV), a rather large value, even for the charmonium-inclusive partial width of such a state. Predictions of the partial decay widths of Y(3940) based on a $\mathrm{D}^*\bar{\mathrm{D}}^*$ bound-state model [11] obtains a product roughly compatible to the present measurement.

4 The Y(4140) and X(4350)

Using exclusive $\mathrm{B}^+\to\mathrm{J}/\psi\phi\mathrm{K}^+$ decays, the CDF Collaboration observed a narrow structure near the $\mathrm{J}/\psi\phi$ mass threshold ($m_{\mathrm{J}/\psi}+m_\phi=4.117$ GeV$/c^2$) with a statistical significance of 3.8σ [13]. The mass and width of this structure are fitted to be $4143.0\pm2.9\pm1.2$ MeV and $11.7^{+8.3}_{-5.0}\pm3.7$ MeV, respectively using an S-wave relativistic BW function. Assuming isospin conservation, this new state, called Y(4140) by the CDF Collaboration, is an isospin singlet state with positive C and G parities since the quantum numbers of both J/ψ and φ are $I^G(J^{PC})=0^-(1^{--})$. It was argued by the CDF Collaboration that the Y(4140) can not be a conventional charmonium state, because a charmonium state with mass about 4143 MeV would dominantly decay into open charm pairs, and the branching fraction into the doubly OZI (Okubo-Zweig-Iizuka) forbidden modes J/ψφ or J/ψω would be negligible.

There have been a number of different interpretations proposed for the Y(4140), including a $\mathrm{D}_s^{*+}\mathrm{D}_s^{*-}$ molecule [11, 14–20], an exotic 1^{-+} charmonium hybrid [16], a $\mathrm{c\bar{c}s\bar{s}}$ tetraquark state [21], or a natural consequence of the opening of the φJ/ψ channel [22]. There are also arguments that the Y(4140) should not be a conventional charmonium χ''_{c0} or χ''_{c1} [23], nor a scalar $\mathrm{D}_s^{*+}\mathrm{D}_s^{*-}$ molecule since QCD sum rules [24, 25] predict masses inconsistent with the observed mass.

The Belle Collaboration searched for this state using the same process with 772×10^6 $\mathrm{B\bar{B}}$ pairs. Fig. 2 shows the φJ/ψ invariant mass distribution with the energy difference $\Delta E=E_{\mathrm{B}}-E_{\mathrm{beam}}$ restricted to the range $|\Delta E|<40$ MeV, where E_{B} is the center-of-mass (CM) energy of the B candidate and E_{beam} is the CM beam energy. No significant Y(4140) signal was found. From the fit with the mass and width of the Y(4140) fixed to the CDF measurements, we obtain $7.5^{+4.9}_{-4.4}$ signal events. The statistical significance of the Y(4140) is estimated to be 1.9σ and the upper limit on the production rate $\mathcal{B}(\mathrm{B}^+\to\mathrm{Y}(4140)\mathrm{K}^+)\mathcal{B}(\mathrm{Y}(4140)\to\mathrm{J}/\psi\phi)$ is measured to be 6×10^{-6} at the 90% C.L. Although this upper limit is lower than the central value of the CDF measurement $(9.0\pm3.4\pm2.9)\times10^{-6}$, it does not contradict the CDF measurement considering the large error [13].

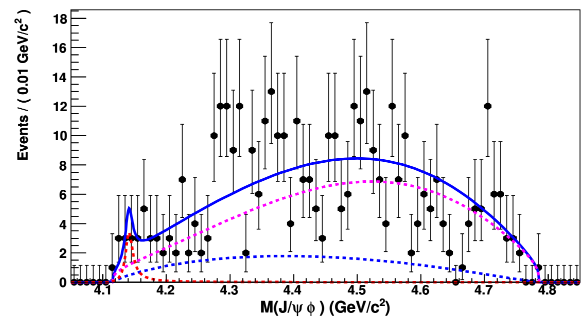

Fig. 2. Fit to the φJ/ψ invariant mass distribution with the mass and width of the Y(4140) fixed to the CDF measurements within $|\Delta E|<$ 40 MeV region.

Assuming the Y(4140) is a $\mathrm{D}_s^{*+}\mathrm{D}_s^{*-}$ molecule with quantum number $J^{PC}=0^{++}$ or 2^{++}, the authors of Ref. [11] predicted a two-photon partial width of the Y(4140) of the order of 1 keV, which is large and can be tested with experimental data. The Belle Collaboration searched for this state in two-photon production [26] to test this model. This analysis is based on a 825 fb^{-1} data sample collected at the $\Upsilon(nS)$ ($n=1,3,4,5$) resonances. No Y(4140) signal is observed, and the upper limit on the product of the two-photon decay width and branching fraction of Y(4140) → φJ/ψ is measured to be $\Gamma_{\gamma\gamma}(\mathrm{Y}(4140))\mathcal{B}(\mathrm{Y}(4140)\to\phi\mathrm{J}/\psi)<39$ eV for $J^P=0^+$, or <5.7 eV for $J^P=2^+$ at the 90% C.L. for the first time. The upper limit on $\Gamma_{\gamma\gamma}(\mathrm{Y}(4140))\mathcal{B}(\mathrm{Y}(4140)\to\phi\mathrm{J}/\psi)$ from this experiment is lower than the prediction of 176^{+137}_{-93} eV for $J^{PC}=0^{++}$, or 189^{+147}_{-100} eV for $J^{PC}=2^{++}$ (calculated by using the numbers in Ref. [11] and total width of the Y(4140) from CDF measurement [13]). This disfavors the scenario of the Y(4140) being a $\mathrm{D}_s^{*+}\mathrm{D}_s^{*-}$ molecule with $J^{PC}=0^{++}$ or 2^{++}.

Evidence is reported for a narrow structure at 4.35 GeV$/c^2$ in the φJ/ψ mass spectrum in the above two-photon process $\gamma\gamma\to\phi\mathrm{J}/\psi$ (see Fig. 3) in the

Belle experiment. In order to obtain the resonance parameters of the structure at 4.35 GeV/c^2, an unbinned extended maximum likelihood method is applied to the ϕJ/ψ mass spectrum. The distribution is fitted in the range 4.2 to 5.0 GeV/c^2 with an acceptance-corrected BW function convoluted with a double Gaussian resolution function as the signal shape and a constant term as the background shape. The shape of the double Gaussian resolution function is obtained from MC simulation.

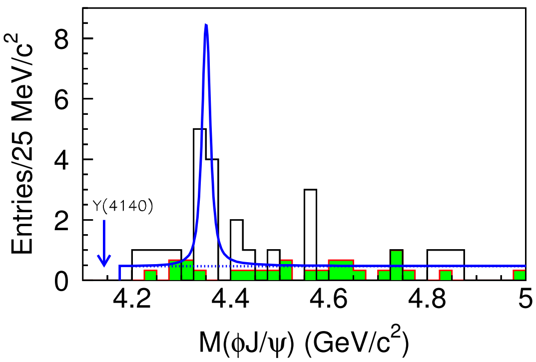

Fig. 3. The ϕJ/ψ invariant mass distribution of the final candidate events in the $\gamma\gamma \to$ ϕJ/ψ process. The blank histogram is the experimental data. The fit to the ϕJ/ψ invariant mass distribution from 4.2 to 5.0 GeV/c^2 is described in the text. The solid line is the best fit, the dashed line is the background, and the shaded histogram is from normalized ϕ and J/ψ mass sidebands. The arrow shows the position of the Y(4140).

From the fit, a signal of $8.8^{+4.2}_{-3.2}$ events, with statistical significance of 3.2 standard deviations including systematic uncertainty, is observed. The mass and natural width of the structure (named X(4350)) are measured to be $4350.6^{+4.6}_{-5.1}\pm 0.7$ MeV and $13.3^{+17.9}_{-9.1}\pm4.1$ MeV, respectively. The products of its two-photon decay width and branching fraction to ϕJ/ψ is measured to be $\Gamma_{\gamma\gamma}(\mathrm{X}(4350))\mathcal{B}(\mathrm{X}(4350)\to \phi\mathrm{J}/\psi)=6.4^{+3.1}_{-2.3}\pm1.1$ eV for $J^P=0^+$, or $1.5^{+0.7}_{-0.5}\pm0.3$ eV for $J^P=2^+$. It is noted that the mass of this structure is consistent with the predicted values of a $c\bar{c}s\bar{s}$ tetraquark state with $J^{PC}=2^{++}$ in Ref. [21] and a $\mathrm{D}_s^{*+}\mathrm{D}_{s0}^{*-}$ molecular state in Ref. [27].

5 The charged Z states

Belle's $\mathrm{Z}(4430)^+$ signal is a sharp peak in the $\pi^+\psi(2S)$ invariant mass distribution from $\mathrm{B}\to \mathrm{K}\pi^+\psi(2S)$ decays [28]. A fit using a BW function gives $M=4433\pm4\pm2$ MeV and $\Gamma=45^{+18+30}_{-13-13}$ MeV, with an estimated statistical significance of more than 6σ. Consistent signals are seen in various subsets of the data: i.e. for both the $\psi(2S)\to \mathrm{l}^+\mathrm{l}^-$ and $\psi(2S)\to \pi^+\pi^-\mathrm{J}/\psi$ subsamples, the $\psi(2S)(\mathrm{J}/\psi)\to \mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ subsamples, etc.

However the BABAR group did not confirm the $\mathrm{Z}(4430)^+\to\pi^+\psi(2S)$ mass peak in their partial wave analysis of $\mathrm{B}\to\mathrm{K}\pi\psi(2S)$ decays [29] although statistically BABAR result does not contradict Belle's observation. Belle performed a reanalysis of their data with a similar partial wave analysis. Specifically, they modelled $\mathrm{B}\to\mathrm{K}\pi\psi(2S)$ as the sum of two-body decays $\mathrm{B}\to\mathrm{K}_i^*\psi(2S)$, where K_i^* denotes all of the known $\mathrm{K}^*\to\mathrm{K}\pi$ resonances that are kinematically accessible, both with and without a $\mathrm{B}\to\mathrm{KZ}$ component, where Z denotes a resonance that decays to $\pi\psi(2S)$ [30].

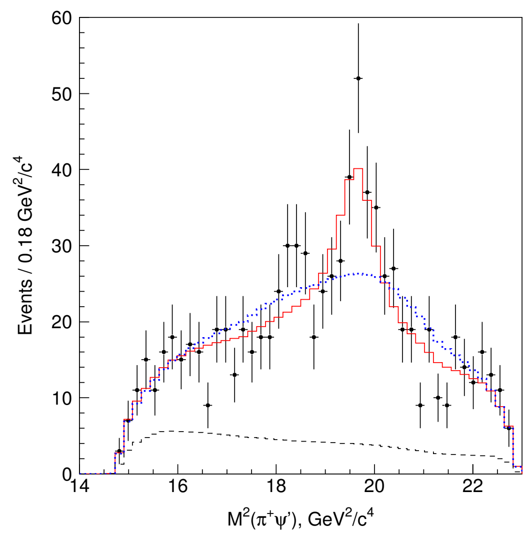

Fig. 4. The data points show the $M^2(\pi\psi(2S))$ projection of the Dalitz plot with the K^* bands removed from $\mathrm{B}\to\mathrm{K}\pi^+\psi(2S)$ decays. The histograms show the corresponding projections of the fits with and without a $\mathrm{Z}\to\pi\psi(2S)$ resonance term.

The data points in Fig. 4 shows the $M^2(\pi\psi(2S))$ Dalitz plot projection with the prominent K^* bands removed compared with the results of the fit with no Z resonance, shown as a dashed histogram, and that with a Z resonance, shown as the solid histogram. The fit with the Z is favored over the fit with no Z by 6.4σ. The fitted mass, $M=4443^{+15+19}_{-12-13}$ MeV, agrees within the systematic errors with the earlier Belle result; the fitted width, $\Gamma=107^{+86+74}_{-43-56}$ MeV, is larger, but also within the systematic errors of the previous result. The product branching fraction from the Dalitz fit: $\mathcal{B}(\mathrm{B}^0\to\mathrm{KZ}^+)\mathcal{B}(\mathrm{Z}^+\to\pi^+\psi(2S))=$

$(3.2^{+1.8+9.6}_{-0.9-1.6})\times10^{-5}$ is not in strong contradiction with the BABAR 95% C.L. upper limit of 3.1×10^{-5}.

In addition to the $Z(4430)^+$, Belle has presented results of an analysis of $B\to K\pi^+\chi_{c1}$ decays that require two resonant states in the $\pi^+\chi_{c1}$ channel [31]. In this case the kinematically allowed mass range for the $K\pi$ system extends beyond the $K_3^*(1780)$ F-wave resonance and S-, P-, D- and F-wave terms for the $K\pi$ system are included in the model. The fit with a single resonance in the $Z\to\pi\chi_{c1}$ channel is favored over a fit with only K^* resonances and no Z by more than 10σ. Moreover, a fit with two resonances in the $\pi\chi_{c1}$ channel is favored over the fit with only one Z resonance by 5.7σ. The fitted masses and widths of these two resonances are: $M_1=4051\pm14^{+20}_{-41}$ MeV and $\Gamma_1=82^{+21+47}_{-17-22}$ MeV and $M_2=4248^{+44+180}_{-29-35}$ MeV and $\Gamma_2=177^{+54+316}_{-39-61}$ MeV. The product branching fractions have central values similar to that for the Z(4430) but with large errors. Fig. 5 shows the $M(\pi\chi_{c1})$ projection of the Dalitz plot with the K^* bands excluded and the results of the fit with no $Z\to\pi\chi_{c1}$ resonances and with two $Z\to\pi\chi_{c1}$ resonances.

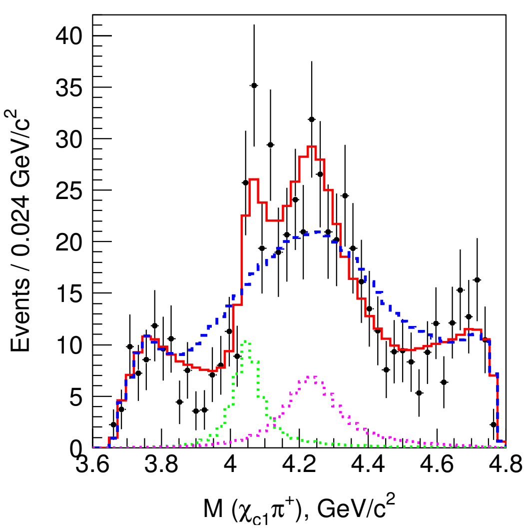

Fig. 5. The data points show the $M(\pi\chi_{c1})$ projection of the Dalitz plot with the K^* bands removed from $B\to K\pi^+\chi_{c1}$ decays. The histograms show the corresponding projections of the fits with and without the two $Z\to\pi\chi_{c1}$ resonance terms.

Since the Z states have hidden charm and light quarks to allow them to decay to charmonium rich final states and with non-zero charge, if any one of them is confirmed, it is an unambiguous evidence for a state with more than three quarks.

6 The X/Y states in $\Upsilon(1S)$ radiative decays

For charge parity even X/Y states, one way to study them is through radiative decays of the Υ states below open-bottom threshold. The production rates of the lowest lying P-wave spin-triplet (χ_{cJ}, J=0, 1, or 2) and S-wave spin-singlet (η_c) have been calculated in Ref. [32], and the former is at a few millionth level while the latter is about 5×10^{-5}. There is no existing calculation of the excited charmonium states, let alone the X(3872), Y(4140) and X(3915).

The Belle Collaboration searched for the X(3872), Y(4140) and X(3915) in $\Upsilon(1S)$ radiative decays [33] based on 5.8 fb^{-1} of data collected at the $\Upsilon(1S)$ and 1.8 fb^{-1} of data collected at 9.43 GeV. In the $\pi^+\pi^-J/\psi$ mode, except for the ISR produced $\psi(2S)$, there are only a few events scatter above the $\psi(2S)$ peak (see Fig. 6). There is only one event in the X(3872) mass region. No X(3872) nor

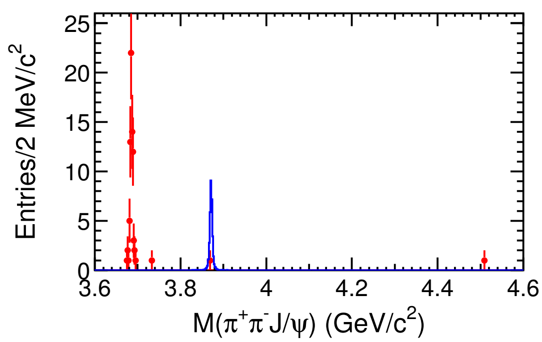

Fig. 6. $\pi^+\pi^-J/\psi$ invariant mass distribution of the selected $\Upsilon(1S)\to\gamma\pi^+\pi^-J/\psi$ candidates. Dots with error bars are data, blank histograms are MC expectation of the signal shape with arbitrary normalization.

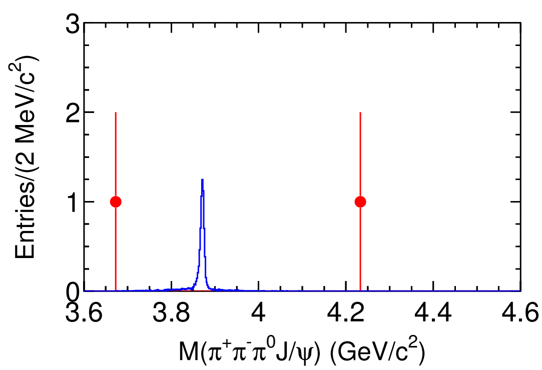

Fig. 7. $\pi^+\pi^-\pi^0J/\psi$ invariant mass distribution of the selected $\Upsilon(1S)\to\gamma\pi^+\pi^-\pi^0J/\psi$ candidates. Dots with error bars are data, blank histograms are MC expectation of the signal shape with arbitrary normalization.

X(3915) signals was observed in the $\pi^+\pi^-\pi^0 J/\psi$ mode (see Fig. 7). Upper limits on the production rates are determined to be $\mathcal{B}(\Upsilon \to \gamma X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 2.2 \times 10^{-6}$, $\mathcal{B}(\Upsilon \to \gamma X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0 J/\psi) < 3.4 \times 10^{-6}$ and $\mathcal{B}(\Upsilon \to \gamma X(3915)) \times \mathcal{B}(X(3915) \to \omega J/\psi) < 3.4 \times 10^{-6}$ at the 90% C.L. respectively. Belle also searched for the Y(4140), but there is no candidate event in the signal region, and the upper limit on the production rate $\mathcal{B}(\Upsilon \to \gamma Y(4140))\mathcal{B}(Y(4140) \to \phi J/\psi))$ is determined to be 2.6×10^{-6} at the 90% C.L.

7 Summary

In summary, there are lots of charmonium-like XYZ states states observed recently in charmonium mass region, but many of them show properties different from the naive expectation of conventional charmonium states. It has been suggested that many of the XYZ states are multiquark states, either tetraquarks or molecules. The problem with the tetraquark explanation is that it predicts multiplets with other charge states that have not been observed, and larger widths than have been observed. The possibility that some of the XYZ states are molecules is likely intertwined with threshold effects that occur when channels are opened up. Including coupled-channel effects and the rescattering of charmed meson pairs in the mix can also result in shifts of the masses of $c\bar{c}$ states and result in meson-meson binding which could help explain the observed spectrum. However, due to limited statistics, the experimental information on the properties of any of these states is not enough for us to draw solid conclusion, let alone our poor knowledge on the QCD prediction of the properties of the exotic states or the usual charmonium states.

Many of the XYZ states need independent confirmation and to understand them will require detailed studies of their properties. With better experimental and theoretical understanding of these states we will have more confidence in believing that any of these new states are non-conventional $c\bar{c}$ states like molecules, tetraquarks, and hybrids. In the near future, the Belle II experiment [34] under construction, with about 50 ab^{-1} data accumulated, will surely improve our understanding of all these states.

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