Hadron Spectroscopy Results from Belle

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We report on the most recent experimental progress on XYZ charmoniumlike meson states and their possible counterparts in the $s\pi$ and $b\bar{b}$ systems.

1. Introduction

The results presented here are based on a data sample collected with the Belle detector [1] at the KEKB asymmetric-energy $e^+e^-$ collider [2]. The experiment is located at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. Electrons and positrons are being collided at the center-of-mass (CM) energy of about 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. The main objective of the Belle experiment is a study of the $CP$ violation in the $B$ meson system produced from $\Upsilon(4S)$, however a large data sample collected with the Belle detector and its excellent performance also make possible to perform searches for new hadronic states as well as studies of their properties. There are several possible mechanisms of the particle production at $B$ factories: production in the $B$ meson decays, fragmentation of quarks in $e^+e^-$ annihilation or two-photon collisions. Most of the newly discovered states, the so-called $XYZ$ mesons, almost certainly contain a $c\bar{c}$ quark pair among their constituent particles but do not fit into any of the unassigned charmonium levels predicted within the potential models. As a result, they are considered to be possible candidates for new, exotic types of particles such as multiquark states that include either molecular states (two loosely bound charm mesons ($c\bar{c}$) or tetraquarks (tightly bound four-quark states, $c\bar{c}q\bar{q}$) [13–16], charmonium hybrids (c-gluon with excited gluonic degrees of freedom) [17–19], or hadro-charmonium (compact charmonium states, $J/\psi$, $\psi(2S)$, $\chi_{c}$, "coated" by excited light-hadron matter) [20]. More conservative models [21–24] suggest to reconsider the effect of the numerous open charm thresholds which are located in many cases near the new states on the parameters of the conventional charmonium levels.

In this paper we review review recent results from Belle collaboration on the $X$, $Y$ and $Z$ charmonium-like meson states as well as on their possible counterparts in $s\pi$ and $b\bar{b}$ systems, summarized also in Table I. Recently the highest luminosity ever reached in $e^+e^-$ collisions was achieved, exceeding $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$. This corresponds to more than 1.5 million $B\bar{B}$ pairs recorded by the Belle detector each day. The integrated luminosity of the total sample collected in 10 years of operation amounts to about 960 fb$^{-1}$. Most of the results presented here are obtained on a smaller data sample.

The detector is configured within a 1.5 T superconducting solenoid and iron structure surrounding the KEKB beams. The Silicon Vertex Detector (SVD), situated just outside a cylindrical beryllium beam-pipe, is used for precise reconstruction of decay vertices. Main charged particle tracking is provided by the Central Drift Chamber (CDC). The relative uncertainty of the measured transverse momentum is between 0.3% and 1.1% for tracks with momenta between 0.6 and 5 GeV/c, respectively. Particle identification is provided by $dE/dx$ ionization energy loss measurements in the CDC, Cherenkov light yield measurements in the Aerogel Čerenkov counters (ACC) and time-of-flight counters (TOF). More than three standard deviations separation between kaons and pions is realized up to momenta of 3 GeV/c. Electromagnetic showers are detected with the Electromagnetic Calorimeter (ECL) that consists of an array of CsI(Tl) crystals which also serve as the identification device of $e^\pm$ and photons. Muons and $K_L$ mesons are identified by arrays of resistive plate counters interspersed in the iron yoke.

3. The $XYZ$ states with masses near 3940 MeV

In 2005, Belle reported observations of three states with masses near 3940 MeV (see Fig. 1): the $X(3940)$, observed in the process $e^+e^- \to J/\psi X(3940)$, both in inclusive production and via the $X(3940) \to D\bar{D}^*$ decay mode [26]; the $Y(3940)$, observed as a near-threshold enhancement in the $\omega J/\psi$ invariant mass distribution for exclusive $B \to K\omega J/\psi$ decays [27]; and the $Z(3930)$, observed as a $D\bar{D}$ mass peak in two-photon collisions $\gamma\gamma \to D\bar{D}$ [28]. The mass and width
Table I Summary of new states observed by Belle [25].

| State   | M (MeV)  | Γ (MeV)  | \(J^{PC}\) | Decay Modes                  | Production Modes    | Also observed by |
|---------|----------|----------|------------|------------------------------|---------------------|------------------|
| \(Y_s(2175)\) | 2175 ± 8 | 58 ± 26  | 1−−        | \(\phi(980)\)               | \(e^+e^-\)          | BaBar, BESII     |
| \(X(3872)\)   | 3871.4 ± 0.6 < 2.3 | 1++      | \(\pi^+\pi^- J/\psi, \gamma J/\psi, DD^*\) | \(B \to X(3872), \bar{p}p\) | BaBar, CDF, D0, |
| \(X(3915)\)   | 3914 ± 4 | 28.9 ± 12 | 0/2++      | \(\omega J/\psi\)            | \(\gamma \gamma \to X(3915)\) |                 |
| \(Z(3930)\)   | 3929 ± 5 | 29 ± 10  | 2++        | \(DD^*\)                     | \(\gamma \gamma \to Z(3940)\) |                 |
| \(X(3940)\)   | 3942 ± 9 | 37 ± 17  | 0±         | \(DD^*\) (not \(DD^*\)) or \(\omega J/\psi\) | \(e^+e^- \to J/\psi X(3940)\) | BaBar, CLEO     |
| \(Y(3940)\)   | 3943 ± 17 | 87 ± 34  | ??         | \(\omega J/\psi\) (not \(DD^*\)) | \(B \to KY(3940)\) | BaBar           |
| \(Y(4008)\)   | 4008.4 ± 8.2 | 226.9 ± 97 | 1−−      | \(\pi^+\pi^- J/\psi\)         | \(e^+e^-\)          | BaBar, CLEO     |
| \(X(4160)\)   | 4156 ± 29 | 139.5 ± 113 | 0±       | \(D^*D^*\) (not \(DD^*\))    | \(e^+e^- \to J/\psi X(4160)\) | BaBar, CLEO     |
| \(Y(4260)\)   | 4261 ± 12 | 83 ± 22  | 1−−        | \(\pi^+\pi^- J/\psi\)         | \(e^+e^-\)          | BaBar           |
| \(Y(4350)\)   | 4361 ± 13 | 74 ± 18  | 1−−        | \(\pi^+\pi^- J/\psi'\)        | \(e^+e^-\)          | BaBar           |
| \(X(4630)\)   | 4634 ± 11 | 92 ± 32  | 1−−        | \(\Lambda^+_c\lambda^-\)      | \(e^+e^-\)          | BaBar           |
| \(Y(4660)\)   | 4664 ± 12 | 48 ± 15  | 1−−        | \(\pi^+\pi^- J/\psi'\)        | \(e^+e^-\)          | BaBar           |
| \(Z(4050)\)   | 4051 ± 23 | 82.5 ± 51 | ?          | \(\pi^\pm \chi_{c1}\)        | \(B \to K\pi\)      |                 |
| \(Z(4250)\)   | 4248 ± 13 | 177.5 ± 120 | ?          | \(\pi^\pm \chi_{c1}\)        | \(B \to K\pi\)      |                 |
| \(Z(4430)\)   | 4433 ± 5 | 45 ± 38  | ?          | \(\pi^\pm J/\psi'\)           | \(B \to K\pi\)      |                 |
| \(Y_b(10890)\) | 10,890 ± 3 | 55 ± 9   | 1−−        | \(\pi^+\pi^- Y(1,2,3S)\)      | \(e^+e^- \to Y_b\)  |                 |

of the \(Z(3930)\) are measured to be \((3929 ± 5.2)\) MeV\(^1\) and \((29 ± 10 ± 2)\) MeV, respectively, and the product of the two-photon decay width and branching fraction of the \(Z(3930)\) is found to be \(\Gamma(Z(3930)) B(Z(3930) \to DD) = 0.18 ± 0.05 ± 0.03\) keV. An angular analysis showed that spin-2 assignment is strongly favored over spin-0 assignment of \(Z(3930)\). All of the above mentioned properties of \(Z(3930)\) match well to expectations for the \(\chi'_{c2}\), a radial excitation of \(2^3P_2\) charmonium state.

Last year Belle confirmed the observation of \(X(3940) \to DD^*\) and reported an observation of a new charmoniumlike state, \(X(4160)\), seen also in the double charmonium production process in \(e^+e^-\) annihilation but decaying into \(D^*\bar{D}^*\) [29] (see Fig. 2). Neither are seen in the experimentally more accessible \(DD^*\) channel. Circumstantial evidence favour \(J^{PC} = 0^+\) assignments for both states, leading to possible interpretation of these two states as \(\eta_c(3S)\) and \(\eta_c(4S)\) conventional charmoniums. However, the problem with this assignment is that potential models predict masses for these charmonium levels to be significantly higher than those measured for the \(X(3940)\) and \(X(4160)\) (given in Table I).

BaBar also observed a near-threshold \(\omega J/\psi\) enhancement in the \(B \to \omega J/\psi K\) decays [30], confirming the Belle result, but obtained lower mass and smaller width and reduced the uncertainty on each by a factor of around 3. The mass and width consistency between the \(Y(3940)\) (seen in \(\omega J/\psi\)) and the \(X(3940)\) (seen in \(DD^*\)) suggests that the observed peaks are different decay modes of the same state. This explanation is unlikely since a 90% CL lower limit of \(B(Y \to \omega J/\psi) B(Y \to DD^*) > 0.71\) set by Belle searching for \(Y(3940) \to DD^*\) in \(B \to DD^*\) K decays [31] is in a contradiction with a 90% CL upper limit \(B(X \to \omega J/\psi) B(X \to DD^*) < 0.58\) from a search for \(X(3940) \to \omega J/\psi\) in \(e^+e^- \to J/\psi \omega J/\psi\) annihilations performed by Belle [26].

The charmonium state with mass above open-charm mass thresholds is expected to dominantly decay to \(DD^*\)\(^1\), which for \(Y(3940)\) were not observed yet. After taking into account also the fact the partial width to \(\omega J/\psi\) for \(Y(3940)\) is well above the measured partial widths for any of the observed hadronic transitions between charmonium states and lack of charmonium levels at the \(Y(3940)\) mass one can conclude that the \(Y(3940)\) is probably not a charmonium state.

### 3.1. Observation of an enhancement in \(\gamma\gamma \to \omega J/\psi\)

Recently Belle reported an enhancement in the cross section for \(\gamma\gamma \to \omega J/\psi\) in the 3.90-3.95 GeV region [32], which may be related to one of the three states discussed above. The selected events with

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\(^1\)Throughout this review, units are used in which \(c = \hbar = 1\).
\[ \chi \text{ recoil} \]

Figure 1: (a) Invariant mass of \( D\bar{D}^* \) produced in two photon reactions \[28\]. (b) Yield of \( B \) mesons in \( B \rightarrow K\omega J/\psi \) as a function of \( M(\omega J/\psi) \) \[27\]. (c) Spectrum of mass recoiling against the \( J/\psi \) \[26\].

Figure 2: (Top) The \( M(D\bar{D}^*) \) invariant mass distribution for the \( e^+e^- \rightarrow J/\psi D\bar{D}^* \) process and (Bottom) the \( M(D^*\bar{D}) \) invariant mass distribution for the \( e^+e^- \rightarrow J/\psi D^*\bar{D} \) process \[29\]. Points with error bars correspond to the signal windows while histograms show the scaled sideband distributions.

\[ \pi^+\pi^-\pi^0 \text{ and } \ell^+\ell^- \text{ invariant masses within }\pm30 \text{ MeV and } \pm25 \text{ MeV wide windows around the nominal masses of the } \omega \text{ and } J/\psi, \text{ respectively, are required to have a total transfer momentum balance of the final state particles less than }100 \text{ MeV in CM system. The two photon CM energy distribution of selected events is shown in Fig. 3. An S-wave Breit-Wigner fit to this enhancement, gives preliminary results for the mass and width of this new state, denoted by } X(3915), \text{ of } M = 3914 \pm 14 \pm 2 \text{ MeV and } \Gamma = 28 \pm 12^{+2}_{-5} \text{ MeV, respectively, where the systematic errors are determined by varying the selection criteria and fitting procedure. The statistical significance of the signal is } 7.1 \text{ standard deviations. The product of the two-photon decay width and the branching fraction for } X \rightarrow \omega J/\psi \text{ is determined to be } \Gamma\gamma \mathcal{B} = 69 \pm 16^{+7}_{-18} \text{ eV (}21 \pm 4^{+6}_{-5} \text{ eV) for assumed } J^P = 0^+ \text{ assignment.}

The preliminary value for the } X(3915) \text{ mass is about } 2 \text{ standard deviations different from that of the } Z(3930) \text{ (see Table I). If one assumes that } X(3915) \text{ and } Z(3930) \text{ are different decay modes of the same state (} \chi'_{c2} \text{ charmonium), then a comparison of the products of the two-photon decay width and corresponding branching fractions yields the ratio of branching fractions } \mathcal{B}(\chi'_{c2} \rightarrow \omega J/\psi)/\mathcal{B}(\chi'_{c2} \rightarrow D\bar{D}) \geq 0.08, \text{ which is quite large for charmonium. On the other hand, there is a good agreement between these preliminary results and the mass and width quoted by BaBar for the } Y(3940), \text{ which is also seen in } \omega J/\psi. \text{ If } X(3915) \text{ is the same state as } Y(3940), \text{ then } J^{PC} = 0^{++}.\]
4. **X(3872)**

In 2003 Belle discovered a charmoniumlike state X(3872) as a narrow peak in the $\pi^+\pi^- J/\psi$ invariant mass distribution from $B^+ \to K^+\pi^+\pi^- J/\psi$ decays [33]. The observation was later confirmed by CDF [34], D0 [35] and BaBar [36] experiments.

Last year Belle presented new results on the X(3872), produced in $B^+ \to X(3872)K^+$, $B^0 \to X(3872)K^0_S$ (first statistically significant observation) and $B^0 \to X(3872)K^+\pi^-$ decays where $X(3872) \to \pi^+\pi^- J/\psi$ [37]. The mass difference between the X states produced in $B^0+/0 \to X(3872)K^{0+/0}$ decays is found to be $\delta M = M_{X_K} - M_{X_{\pi^0}} = +0.18 \pm 0.89 \pm 0.26$ MeV, consistent with zero. The measurement of mass difference between the X states produced in neutral and charged B decays is interesting since in the diquark-antidiquark model of the X(3872), the X produced in $B^+$ decays is interpreted as a $c\bar{c}u\bar{u}$ combination while the X produced in $B^0$ decays is a $c\bar{c}d\bar{d}$ combination, which should differ in mass by $8 \pm 3$ MeV [16]. Combining the charged and neutral B samples the mass of the X(3872) is found to be $M_{X_{\pi^0}}^{Belle} = 3871.46 \pm 0.37 \pm 0.07$ MeV. The world average of all measurements that use the $\pi^+\pi^- J/\psi$ decay mode is $M_{X_{\pi^0}}^{WA} = 3871.46 \pm 0.19$ MeV (dominated by the updated measurement from the CDF [38]) which is just below the of $D^*\bar{D}$ mass threshold: $m_{D^*\bar{D}} = 3871.81 \pm 0.36$ MeV [39]. We also measured the ratio of branching ratios which is found to be $\frac{B(B^+ \to X(3872)K^+)}{B(B^0 \to X(3872)K^0_S)} = 0.82 \pm 0.22 \pm 0.05$ and is consistent with unity.

We also performed a study of X(3872) production in exclusive $B \to X(3872)K^+\pi^-$ decays [37]. We observe a signal of $90 \pm 19$ events. A fit to the $M_{K\pi}$ distribution (see Fig. 4) shows that non-resonant $K\pi$ production dominates over the $K^*(892)^0$ contribution. This is in contrast to what is observed in B decays to conventional charmonium, such as $\psi(2S)$, in association with $K\pi$, in which the resonant $K^*(892)^0$ contribution dominates, as seen in Fig. 4. We measure $B(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times B(X(3872) \to J/\psi+\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ and we set the 90% C.L. limit, $B(B^0 \to X(3872)K^*(892)^0) \times B(X(3872) \to J/\psi+\pi^+\pi^-) < 3.4 \times 10^{-6}$.

The close proximity of the X(3872) to the $D^*\bar{D}$ threshold motivated the interpretation of X(3872) as a $D^{*0}\bar{D}^{*0}$ molecule [3–12] and the search for the $X(3872) \to D^{*0}\bar{D}^{*0}$ decays. In 2005 Belle showed a 6.4σ excess of events in the $D^{*0}\bar{D}^{*0}$ invariant mass channel $B \to D^{*0}\bar{D}^{*0}\pi^0 K$ [40] and BaBar reported an observation of X(3872) decays to $D^{*0}\bar{D}^{*0}$ [41]. The masses of X(3872) measured by both experiments are in agreement, however the weighted average significantly differs from the mass measured in the $\pi^+\pi^- J/\psi$ decay mode. Last year Belle presented an updated study of near-threshold enhancement in the $D^{*0}\bar{D}^{*0}$ invariant mass spectrum in $B \to D^{*0}\bar{D}^{*0}K$ decays [42]. The measured mass, $M = 3872.6_{-0.4}^{+0.5}$ MeV, and width, $\Gamma = 3.9_{-1.3}^{+2.5+0.5}$ MeV, are consistent with the current world average values for the X(3872) in the $\pi^+\pi^- J/\psi$ mode. The obtained branching fraction and width are compatible with the values previously published by Belle in Ref. [40] for non-resonant $D^{*0}\bar{D}^{*0}\pi^0$ decays.

5. Charged charmoniumlike states

5.1. **Z^±(4430)**

The first charged charmoniumlike state, denoted by $Z^+(4430)$, was discovered by Belle in 2007 in the $\pi^+\psi(2S)$ invariant mass distribution for $B \to \psi(2S)K\pi$ decays [43]. The $M_{K\pi}$ distribution of events after vetoing the $K^*(892)^0$ and $K_S^*(1430)^0$ peaks in $M_{K\pi}$ is shown in Fig. 5. A fit to this distribution with an S-wave Breit-Wigner function for $D^0\bar{D}^{*0}$ invariant mass spectrum in $B \to D^0\bar{D}^{*0}K$ decays [42].
the signal and a phase-space-like function for the nonpeaking background gives $M = 4422 \pm 4 \pm 1$ MeV and $\Gamma = 44^{+17}_{-13} \pm 30$ MeV.

BaBar also performed a search for $Z^\pm(4430) \rightarrow J/\psi \pi^\pm$ and $Z^\pm(4430) \rightarrow \psi(2S) \pi^\pm$ in $B \rightarrow J/\psi(\psi(2S)) K \pi^\pm$ decays [44] and reported a 1.9 standard deviations signal with mass and width similar to Belle’s. The significance of the signal increased to 3.1 standard deviations, after fixing the mass and width to the values obtained by Belle. This year Belle reported a full Dalitz plot analysis of $B \rightarrow \psi(2S) K \pi$ decays [45] in order to check whether the dynamics in the $K \pi$ channel can cause mass structures in the $\psi(2S)$ invariant mass distribution that have no relation to $\pi\psi(2S)$ dynamics. The fit to the $M^2_{K\pi}$ vs. $M^2_{\pi\psi(2S)}$ Dalitz plot distribution with the default fit model which includes all known low lying $K \pi$ resonances ($K^*(800)$, $K^*(892)$, $K^*(1410)$, $K^*_2(1430)$, $K^*(1680)$) fails to reproduce the narrow peak around 4.43 GeV in $M_{\pi\psi(2S)}$. The fit quality significantly improves after adding one $\pi\psi(2S)$ resonance ($Z(4430)$) to the default Dalitz model. Figure 6 shows the $M^2_{\pi\psi(2S)}$ Dalitz plot projection with superimposed results of the fits without and with $Z$ resonance. The fit with the $Z$ is favored over the fit with no $Z$ by 6.4 standard deviations. The fitted mass, $M = 4443^{+15}_{-12} \pm 19$ MeV, and width, $\Gamma = 107^{+56}_{-43} \pm 74$ MeV agree within systematic errors with the previous Belle result. A detailed systematic study is performed by considering a variety of other fit hypothesis. In all cases the significance of the $Z(4430)$ is found to be larger than 5.4 standard deviations. The product branching fraction from the Dalitz fit: $B^0 \rightarrow K^+ \pi^- \psi(2S)$ is performed by considering a variety of other fit hypothesis. A detailed systematic study was performed to obtain an upper limit of $3 \times 10^{-5}$ for the $K^- Z^+ \rightarrow B(\pi^+ \psi(2S)) = (3.2^{+1.8}_{-0.5} \pm 0.3) \times 10^{-5}$ is not in strong contradiction with the BaBar 95% CL upper limit of $3.1 \times 10^{-5}$.

### 5.2. $Z^\pm(4050)$ and $Z^\pm(4250)$

In addition to the $Z^+(4430)$, Belle has discovered two new charged charmoniumlike states in the $\pi^+ \chi_{c1}$ channel of $B \rightarrow K \pi^+ \chi_{c1}$ decays [46]. The Dalitz plot of selected events is shown in Fig. 7 and exhibits some distinct features: two vertical bands at around 0.8 GeV^2 and 2 GeV^2, corresponding to two-body $K^+(892) \chi_{c1}$ and $K^+(1430)^0 \chi_{c1}$ decays, respectively, and a distinct horizontal band around 17 GeV^2, indicating a structure in the $\pi^+ \chi_{c1}$ channel. To describe the decay dynamics in the $K \pi$ channel we included the following eight $K^*$ resonances: $K^*(800)$, $K^*(892)$, $K^*(1410)$, $K^*_2(1430)$, $K^*(1680)$) and $K^*_3(1780)$. The result of the fit with $K \pi$ dynamics only is shown as a dashed histogram in Fig. 7. It fails to describe the observed $M^2_{\pi\chi_{c1}}$ distribution. The fit with a single new $Z$ resonance in the $\pi\chi_{c1}$ channel is favored over the fit with only $K^*$ resonances and no $Z$ by more than 10 standard deviations. Moreover, a fit with two $Z$ resonances is favored over the fit with only one $Z$ resonance by 5.7 standard deviations (the fit result with two $Z$ resonances included is shown in Fig. 7). We also tried to fit with many different $K \pi$ resonance options, including the addition of new resonances with floating masses and widths, however no model with
Table II Masses, widths and product branching fractions of \( Z^+(4050) \) and \( Z^+(4250) \) observed in \( B \to K\pi^+\chi_{c1} \) decays.

| \( M \) [MeV] | \( \Gamma \) [MeV] | \( \mathcal{B}(B \to K^+\pi^-) \) | \( \mathcal{B}(Z^+ \to \pi^+\chi_{c1}) \) [10^{-5}] |
|----------------|----------------|------------------|-----------------------------|
| \( Z(4050)^+ \) | \( 4051^{+14}_{-13} \) | 3.0^{+1.5}_{-0.8} | \( 4.0^{+2.3}_{-0.9} \) |
| \( Z(4250)^+ \) | \( 4248^{+14}_{-13} \) | 21^{+5}_{-4} | \( 17^{+4}_{-3} \) |

Nonzero electric charge makes these three states especially for the lower-mass side of the \( Y(4260) \) state and in addition found another resonant structure, called \( Y(4008) \). A fit using two interfering Breit-Wigner amplitudes to the \( \pi^+\pi^-J/\psi \) invariant mass distribution describes the data better than a fit assuming one resonance, especially for the lower-mass side of the 4.26 GeV/c² enhancement (see Fig. 8(a)). Obtained masses and widths of the \( Y(4008) \) and \( Y(4260) \) are given in Table I.

6.1 \(-\) states via ISR

ISR has proven to be powerful tool to search for \( 1^- \) states at B-factories, since it allows to scan a broad energy range of \( \sqrt{s} \) below the initial \( e^+e^- \) CM energy, while the high luminosity compensates for the suppression due to the hard-photon emission.

6.1. \( Y(4008) \) and \( Y(4260) \)

First state, discovered with the ISR technique by BaBar, was \( Y(4260) \) in the \( e^+e^- \to \gamma_{\text{ISR}}Y(4260) \to \gamma_{\text{ISR}}\pi^+\pi^-J/\psi \) process [47]. Using the same method Belle confirmed the \( Y(4260) \) state and in addition found another resonant structure, called \( Y(4008) \) [48]. A fit using two interfering Breit-Wigner amplitudes to the \( \pi^+\pi^-J/\psi \) invariant mass distribution describes the data better than a fit assuming one resonance, especially for the lower-mass side of the 4.26 GeV/c² enhancement (see Fig. 8(a)). Obtained masses and widths of the \( Y(4008) \) and \( Y(4260) \) are given in Table I.

6.2. \( Y(4325) \) and \( Y(4660) \)

The BaBar collaboration subsequently reported a similar structure in the cross section for the ISR \( e^+e^- \) annihilation process resulting in the \( \pi^+\pi^-\psi(2S) \) final state [49]. The mass and width of the state denoted as \( Y(4325) \) are both significantly higher than the values found for the \( Y(4260) \). Belle performed a similar study on a larger data sample (673 fb\(^{-1}\) for Belle compared to 272 fb\(^{-1}\) for BaBar) and observed that the structure is formed from two narrower peaks [50]; one, in agreement with the BaBar study, is observed near 4.36 GeV/c² and another, called \( Y(4660) \), near 4.66 GeV/c². Fit to the \( \pi^+\pi^-\psi(2S) \) distribution with a coherent sum of two Breit-Wigner amplitudes is shown in Fig. 8(b). Fitted masses and widths of the two states are given in Table I. No sign was found either of \( Y(4260) \) (\( Y(4008) \)) decay to \( \pi^+\pi^-\psi(2S) \), or
of $Y(4325)$ ($Y(4660)$) decay to $\pi^+\pi^-J/\psi$.

The nature of $Y$ states still remains unclear. There is only one unassigned $1^{--}$ charmonium level in this mass region, the $3^3D_1$ level, which might accommodate the $Y(4660)$, however there are no other available charmonium level in the spectrum for all other peaks discussed above. In addition, these states, if considered to be conventional charmonium states, should decay mainly to $D^{(*)}D^{(*)}$, however measurements of cross sections for exclusive open-charm final states in this energy range, performed by Belle [51–53], BaBar [54] and CLEO-c [55], shown no evidence for peaking near the masses of the $Y$ states.

6.3. $X(4630)$

The one exception is $e^+e^- \rightarrow \gamma_{ISR}\Lambda^+_c\Lambda^-_c$, for which Belle has reported a near-threshold enhancement, called the $X(4630)$ (see Fig. 9). The fitted mass and width are given in Table I and are consistent within errors with the mass and width of the $Y(4660)$ state.

7. $XY$ counterparts in $b\bar{b}$ and $s\bar{s}$ systems

An interesting question is whether or not there exist any $XY$ counterpart states in the $s\bar{s}$ and $b\bar{b}$ systems, predicted by many of the models proposed to explain the charmoniumlike $XYZ$ states. Some recent results, discussed below, indicate that this may be the case.
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for the ISR processes $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^-\phi(1020)$ and $e^+e^- \rightarrow \gamma_{ISR} f_0(980)\phi(1020)$ with CM energy ranging from 1.5 to 3.5 GeV [59]. Figure 10 shows observed $\pi^+\pi^-\phi(1020)$ and $f_0(980)\phi(1020)$ cross section distributions. The former is fitted with two coherent Breit-Wigner functions and the latter with one Breit-Wigner function interfering with a non-resonant continuum function. The mass and width of the high mass peak, corresponding to $Y(2175)$, are found to be $M = 2079 \pm 13^{+70}_{-28}$ MeV and $\Gamma = 192 \pm 23^{+8}_{-61}$ MeV, which are consistent with the previous measurements. First measurements of mass and width are reported for the low mass peak in the $\pi^+\pi^-\phi(1020)$ cross section distribution, which corresponds to the $\phi(1680)$. They are found to be $M = 1689 \pm 7 \pm 10$ MeV and $\Gamma = 211 \pm 14 \pm 19$ MeV. The widths of the $\phi(1680)$ and $Y(2175)$ are found to be quite similar and both are at the 200 MeV level. This may suggest that the $Y(2175)$ is an excited $1^- \pi \pi$ state. Since the $f_0(980)$ is thought to have a large $\pi \pi$ component, $Y(2175) \rightarrow f_0(980)\phi(1020)$ can be viewed as an open-flavor decay as opposed to $Y(4260) \rightarrow \pi^+\pi^- J/\psi$, which is a hadronic transition. Studies of $Y(2175)$ in other decay modes are needed to distinguish, whether $Y(2175)$ is a conventional $\pi \pi$ state or an $s$-quark counterpart of the $Y(4260)$.

7.2. $Y_b(10890)$

Belle and BaBar measured the partial decay widths of the order of few keV for $Y(4S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ as well as $\pi^+\pi^- \Upsilon(2S)$ [60, 61] and found that are similar to those from dipion transitions from the $\Upsilon(3S)$ to the $\Upsilon(2S)$ and $\Upsilon(1S)$ [39]. The same measurement was also performed by Belle on a data sample at the CM energy of 10.87 GeV, corresponding to the $\Upsilon(5S)$, and found huge signals for $\pi^+\pi^- \Upsilon(1S)$, $\pi^+\pi^- \Upsilon(2S)$ and $\pi^+\pi^- \Upsilon(3S)$ (see Fig. 11). Assuming the observed signal events are due solely to the $\Upsilon(5S)$ resonance, than the corresponding partial widths are found to be in the range (0.52-0.85) MeV, more than two orders of magnitude larger than the corresponding partial widths for $Y(4S)$, $Y(3S)$ and $Y(2S)$ decays to $\pi^+\pi^- \Upsilon(1S)$. A possible explanation is a $b\bar{b}$ counterpart to the $Y(4260)$, denoted as $Y_b$ [63], which may overlap with the $\Upsilon(5S)$. Alternative explanations include a nonperturbative approach for the calculation of the decay widths of dipion transitions of heavy quarkonia [64], the presence of final state interactions [65], or the existence of a tetraquark intermediate state [66].

In order to distinguish these hypotheses Belle performed a measurement of the energy dependence of the cross sections for $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)$ ($n = 1, 2, 3$) at energies around 10.87 GeV [67]. Peaks are found in all three channels at around 10.899 GeV. The preliminary values for the peak mass and width, obtained by performing a fit with a common Breit-Wigner function to the measured $\pi^+\pi^- \Upsilon(nS)$ cross section distribution (shown in Fig. 12), are found to be $M = 10889.6 \pm 1.8 \pm 1.6$ MeV and $\Gamma = 54.7^{+5.5}_{-4.2} \pm 2.5$ MeV. A fit using the PDG resonance parameters for the $\Upsilon(5S)$ and $\Upsilon(6S)$ [39], shown in Fig. 12(b), fails to describe the observed $\pi^+\pi^- \Upsilon(nS)$ cross section.

8. Summary

The Belle experiment at the KEKB collider provides an excellent environment for charmonium spectroscopy. As a result, many new particles, summarized in Table I, have been discovered during the ten year operation of the Belle detector.

We have reported on a new Belle $X(3915) \rightarrow \omega J/\psi$ mass peak in $\gamma\gamma \rightarrow J/\psi$. The measured $X(3915)$ mass and width are in agreement with the BaBar’s mass and width values for the $Y(3940) \rightarrow J/\psi$ resonance seen in $B \rightarrow K\omega J/\psi$ decays. The problem
with the interpretation of this state as a conventional charmonium is its large partial decay width to $\omega J/\psi$.

The mass of the $X(3872)$ produced in $B^0 \to K^0 X(3872)$ and $B^+ \to K^+ X(3872)$ are found to be consistent within around 0.9 MeV. The mass of the $X(3872)$ decaying into $DD^*$ final state is consistent with that from $\pi^+\pi^- J/\psi$ within uncertainties. Another feature of $X(3872)$ is that the non-resonant $K^+\pi^-$ contribution in $B^0 \to K^+\pi^- X(3872)$ decay dominates over the resonant $K^{*0}$ contribution, which is not the case for conventional charmonium states.

There are too many $1^{--}$ $Y$ states and too few unassigned charmonium levels between 4.0 GeV and 4.7 GeV. In addition measurements of cross sections for exclusive open-charm final states in this energy range show no evidence for peaking near the masses of the $Y$ states, except for $e^+e^- \to \Lambda_c^+\Lambda_c^-$, which has a threshold peak near the $Y(4660)$ peak mass.

Three charged $Z$ states were reported by Belle. Their quark content is $\bar{c}d$ which makes them manifestly exotic. It is important that the Belle results get confirmed by other experiments.

Belle reported evidence for possible analogue of $ss$ and $bb$ systems. The $Y_1(10890)$ found in $\pi^+\pi^- Y(nS)$ decays has different structure than $\Upsilon(5S)$.

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