Hadron spectroscopy from B-factories[*]

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Abstract   We review the recent experimental results on hadron spectroscopy from B-factories focusing on the exotic charmonium-like states. Among them we discuss the X(3872), Y(3940), Z(4430)$^+$, Z(4050)$^+$, Z(4250)$^+$ and Y(4140) states found in B-meson decays, the X(3940) and X(4160) states produced in double charmonium production, the Y(4260), Y(4325), Y(4660) and X(4630) states produced with initial-state radiation in e$^+$e$^-$ annihilation and the X(3915), Y(4350) states observed in two-photon collisions.

Key words   hadron spectroscopy, charmonium, charmonium-like states, charm mesons, cross section

PACS   13.66.Bc, 13.87.Fh, 14.40.Lb

1   Introduction

Recent intensive development of hadron spectroscopy became possible due to a very high luminosity of B-factories, constructed to search for CP-violation in B mesons. Using various possible mechanisms of particle production at at center-of-mass energy near 10.6 GeV, the Belle and BABAR collaborations have made significant contributions to charm, charmonium and bottomonium spectroscopy. As it is impossible to cover such a wide field in a short review, we discuss here only the most puzzling charmonium spectroscopy. The other topics could be found in Ref. [1].

The first charmonium state J/ψ(1S), the bound system consisting of the charmed quark c and antiquark $\bar{c}$, was discovered in 1974 [2]. Nine more charmonium states, the η_c(1S), χ_{c0}(1P), χ_{c1}(1P), χ_{c2}(1P), ψ(2S), ψ(3770), ψ(4040), ψ(4160) and ψ(4415) were observed shortly afterwards. During the next two decades no other charmonium states were found. A new charmonium era started in 2003. During the past six years numerous charmonium-like states were discovered. Among them, only the h_c(1P) [3], η_c(2S) [4] and Z(3930) $\equiv \chi_{c2}$(2P) [5] have been identified as candidates for conventional charmonium, while a number of other states with masses above open charm threshold[2)], the X(3872) [6],

the Y(3940) [7] and X(3915) [8], the Z(4430)$^+$ [9], Z(4050)$^+$, and Z(4250)$^+$ [10], the Y(4260) [11], Y(4325) [12] and Y(4660) [13], the X(4630) [14] and the X(3940) [15] states, have serious problems with a charmonium interpretation.

There are a variety of theoretical explanations for the new states. Conservative models [16] suggest to reconsider the effect of the numerous open charm thresholds on the parameters of the conventional c$\bar{c}$ states predicted within the potential models. However, most recent approaches admit the existence of exotic states in the charmonium-like spectrum. Among them are the models suggesting multiquark states that include either molecular states [17], or tetraquarks [18], charmonium hybrids [19] and hadrocharmonium [20].

2   The X(3872) state

The narrow charmonium-like state X(3872) produced in the exclusive decay B$^+$ $\to$ K$^+\pi^+\pi^-$J/ψ[3)] was discovered by Belle in 2003 [6] with a statistical significance of 10.3σ. The mass of this state, which decays in $\pi^+\pi^-$J/ψ, was measured to be (3872.0 $\pm$ 0.6$\pm$0.5) MeV/c^2 in close proximity to the $M_{D^0}+M_{D^{*0}}$ mass threshold. The width of the X(3872) was found to be surprisingly small: Γ < 2.3 MeV at the 90% C.L. The existence of the X(3872) was confirmed by

CDF [21] and D0 [22], which observed of a $\pi^+\pi^- J/\psi$ resonance consistent with X(3872) produced inclusively in $p\bar{p}$ collisions, and by BABAR [23] who found X(3872) in $B^+ \to K^+\pi^+\pi^- J/\psi$ decays.

It was found by Belle [6] and confirmed by CDF [24] that the $\pi^+\pi^-$ invariant masses concentrate near the upper kinematic boundary that corresponds to the ρ^0 meson mass. Charmonium decays to $\rho^0 J/\psi$ violate isospin and are expected to be strongly suppressed. Observation of the decay X(3872) $\to J/\psi\gamma$ [25, 26] and indications of the decay X(3872) $\to \omega J/\psi$ fix $C_X = +1$ and confirm that the decay X(3872) $\to \pi^+\pi^- J/\psi$ proceeds via $\rho^0 J/\psi$. Spin-parity analysis of the X(3872) in the final state $\mu^+\mu^-\pi^+\pi^-$ performed by CDF [27] demonstrated that only C-even assignments $J^{PC} = 1^{++}$ and 2^{-+}, with decay via $J/\psi\rho^0$ in both cases, describe the data. Belle measurements [28] favor quantum numbers $J^{PC} = 1^{++}$.

Neither the $\chi_{c1}(2P)$ (corresponding to $J^{PC} = 1^{++}$) nor the η_{c2} (corresponding to $J^{PC} = 2^{-+}$) are expected to have such a large branching fraction for the decay to the isospin violating $\rho^0 J/\psi$ mode. Moreover, the mass of the X(3872) is $\sim 100\,\mathrm{MeV}/c^2$ smaller than the expected $\chi_{c1}(2P)$ mass. The most popular option for the X(3872) interpretation is an S-wave $D^0\overline{D}^{*0}$ molecular state [29]. This proposal is motivated by the proximity of the X(3872) to the $D^0\overline{D}^{*0}$ threshold: $M_X \sim M_{D^0} + M_{D^{*0}} = (3871.81 \pm 0.25)\,\mathrm{MeV}/c^2$ [30]. Other options for an X(3872) are tetraquark states [31], hybrids [32] or threshold effects [33].

In 2008 BABAR updated the measurement of X(3872) $\to J/\psi\gamma$ and reported a new decay mode, X(3872) $\to \psi(2S)\gamma$ [34]. The branching fraction $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$ is in agreement with previous measurements [25, 26], while $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma) = (9.9 \pm 2.9 \pm 0.6) \times 10^{-6}$ is found to be unexpectedly large. According to Ref. [35] this measurement is inconsistent with a pure $D^0\overline{D}^{*0}$ molecule interpretation of X(3872) and favors the model assuming mixing of a $D^0\overline{D}^{*0}$ molecule with a conventional charmonium state.

As a check of the tetraquark hypothesis, BABAR searched for a charged partner of the X(3872) in the decay $B \to X(3872)^- K$, X(3872)$^- \to J/\psi\pi^-\pi^0$ [36]. The obtained upper limits on the production of charged X(3872) partners found to be $\mathcal{B}(B^0 \to X(3872)^- K^+) \times \mathcal{B}(X(3782)^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$ at the 90% C.L. and $\mathcal{B}(B^- \to X(3872)^- K_S^0) \times \mathcal{B}(X(3872)^- \to J/\psi\pi^-\pi^0) < 22 \times 10^{-6}$ at the 90% C.L.

exclude an isovector hypothesis for the X(3872).

The diquark-diantiquark model [31] predicts that the observed X(3872) is one component of a doublet of states. In this model, the X(3872) produced in charged B decays would have a mass that is different from its counterpart in neutral B decays by $\Delta M = (7 \pm 2)/\cos(2\theta)\,\mathrm{MeV}/c^2$, where θ is a mixing angle that is near $\pm 20°$. In order to test this hypothesis, both BABAR [37] and Belle [38] performed studies of the X(3872), produced in $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K_S^0$ decays, where X(3872) $\to J/\psi\pi^+\pi^-$. The ratios of the branching fractions $\mathcal{B}(B^0 \to X(3872)K^0)/\mathcal{B}(B^+ \to X(3872)K^+)$ found to be $0.41 \pm 0.24 \pm 0.05$ (BABAR) and $0.82 \pm 0.22 \pm 0.05$ (Belle) are consistent with unity. The mass difference between the X(3872) states from charged and neutral B decay modes, $\Delta M \equiv M_{XK^+} - M_{XK^0}$, is found to be $(2.7 \pm 1.6 \pm 0.4)\,\mathrm{MeV}/c^2$ (BABAR) and $(0.18 \pm 0.89 \pm 0.26)\,\mathrm{MeV}/c^2$ (Belle) is consistent with zero.

In addition, Belle searched for the X(3872) in the decay $B^0 \to X(3872)K^+\pi^-$, X(3872) $\to J/\psi\pi^+\pi^-$ [38] and measured $\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{\mathrm{nonres}}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$. Unlike conventional charmonium the resonant contribution is found to be unexpectedly small: $\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$ at the 90% C.L.

To test the hypothesis that the X(3872) signal observed in the $\pi^+\pi^- J/\psi$ decay mode contains two different states, CDF [39] performed a study of the X(3872) line shape. If there are two overlapping resonances, their mass splitting was found to be $\Delta M < 3.2(3.6)\,\mathrm{MeV}/c^2$ at the 90% (95%) C.L., assuming an equal fraction for the two states in the peak. The measured X(3872) mass value by CDF, $M_X = (3871.61 \pm 0.16 \pm 0.19)\,\mathrm{MeV}/c^2$, is the most precise mass measurement at the current time.

In 2005 Belle showed a 6.4σ excess of events in the $D^0\overline{D}^0\pi^0$ invariant mass in the channel $B \to D^0\overline{D}^0\pi^0 K$, with a mass of $(3875.2 \pm 0.7^{+0.9}_{-1.8})\,\mathrm{MeV}/c^2$ [40]. In 2008 BABAR reported an observation of X(3875) decays to $D^0\overline{D}^{*0}$ [41] with the mass $(3875.1^{+0.7}_{-0.5} \pm 0.5)\,\mathrm{MeV}/c^2$. The weighted average was 4.5σ away from the mass measured in the $J/\psi\pi^+\pi^-$ decay mode. In 2008 Belle presented an updated study of the near-threshold 8.8σ enhancement in the $D^0\overline{D}^{*0}$ invariant mass spectrum in $B \to D^0\overline{D}^{*0}K$ decays [42]. The measured mass $(3872.6^{+0.5}_{-0.4} \pm 0.4)\,\mathrm{MeV}/c^2$ and width are consistent with the current world average values for the X(3872) in the $\pi^+\pi^- J/\psi$ mode [30]. Recently it was shown [43] that the BABAR data [41] prefer the dy-

namically generated virtual state in the DD* system, while the new Belle data [42] clearly indicate a sizable $c\bar{c}$ 2^3P_1 component in the X(3872) wave function.

In spite of a large amount of accumulated experimental data and numerous theoretical approaches, the nature of X(3872) state remains to be established.

3   ISR family with $J^{PC} = 1^{--}$

An entire family of unexpected charmonium-like states with masses above open charm threshold were discovered in the $e^+e^- \to \pi^+\pi^- J/\psi(\psi(2S))\gamma_{ISR}$ processes. (Measured masses and widths of the Y states are presented in Table 1.) The production via initial-state radiation (ISR) fixes the quantum numbers of these states to be $J^{PC} = 1^{--}$.

Table 1.   Measured parameters of the Y states.

state	$M/(\mathrm{MeV}/c^2)$	$\Gamma_{\mathrm{tot}}/\mathrm{MeV}$	decay
Y(4008) [44]	$4008\pm40^{+114}_{-28}$	$226\pm44\pm87$	$\pi\pi J/\psi$
Y(4260) [11]	$4259\pm8^{+2}_{-6}$	$88\pm23^{+6}_{-4}$	$\pi\pi J/\psi$
Y(4260) [45]	$4252\pm6^{+2}_{-3}$	$105\pm18^{+4}_{-6}$	$\pi\pi J/\psi$
Y(4260) [44]	$4247\pm12^{+17}_{-32}$	$108\pm19\pm10$	$\pi\pi J/\psi$
Y(4325) [12]	4324 ± 24	172 ± 33	$\pi\pi\psi(2S)$
Y(4325) [13]	$4361\pm9\pm9$	$74\pm15\pm10$	$\pi\pi\psi(2S)$
Y(4660) [13]	$4664\pm11\pm54$	$48\pm15\pm3$	$\pi\pi\psi(2S)$
X(4630) [14]	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}	$\Lambda_c^+\Lambda_c^-$

The first state, called the Y(4260)[1], was discovered by BABAR as an accumulation of events near 4.26 GeV/c^2 in the invariant mass spectrum of $\pi^+\pi^- J/\psi$ [11]. The new resonance was confirmed by CLEO [46, 47] and Belle [44]. In addition Belle has found another wide cluster of events in the $\pi^+\pi^- J/\psi$ invariant mass distribution, around 4.0 GeV/c^2, called the Y(4008) [44]. In 2008 BABAR presented an update of the Y(4260) resonance study and did not confirm the broad structure around 4.0 GeV/c^2 [45].

Another structure, called the Y(4325)[2], was observed by BABAR in the $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross-section near 4.32 GeV/c^2 [12]. Belle performed a similar study [13] and claimed the existence of two resonant structures, one, in agreement with the BABAR study, near 4.36 GeV/c^2 and another, called Y(4660), near 4.66 GeV/c^2. No sign was found either of the Y(4260) (Y(4008)) decay to $\pi^+\pi^-\psi(2S)$, or of the Y(4325) (Y(4660)) decay to $\pi^+\pi^- J/\psi$. Partial widths of Y decay channels to charmonium plus light hadrons are found to be much larger than those usual for conventional charmonium states.

The observation of the Y(4260) motivated numerous measurements of exclusive e^+e^- cross sections for open charm near threshold. Belle presented the first results of the exclusive e^+e^- cross sections to $D\overline{D}$ ($D = D^0$ or D^+), D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ final states using ISR [48–51]. BABAR has measured cross sections for $e^+e^- \to D^{(*)}\overline{D}^{(*)}$ using ISR [52, 53]. CLEO-c performed a scan over the energy range from 3.97 to 4.26 GeV and measured exclusive cross sections for $D_{(s)}\overline{D}_{(s)}$, $D_{(s)}\overline{D}^*_{(s)}$ and $D^*_{(s)}\overline{D}^*_{(s)}$ final states [54]. Surprisingly, no evidence for open charm production associated with any of the Y states (which is expected for a conventional charmonium with such large masses and widths) has been observed.

The absence of available $J^{PC} = 1^{--}$ charmonium levels for the Y states is another problem for their interpretation. To resolve this problem some models calculate ψ levels with shifted masses [55]. Coupled-channel effects and re-scattering of charm mesons are other possible ways to explain the observed peaks [56]. Other suggestions are hybrids [57], hadro-charmonium [20]; tetraquark [58], $D\overline{D}_1$ or $D^0\overline{D}^{*0}$ molecules [59].

In 2008 Belle has reported a significant near-threshold enhancement in the $e^+e^- \to \Lambda_c^+\Lambda_c^-$ exclusive cross section, called the X(4630) [14]. Both the mass and width of the X(4630) (Table 1) are consistent within errors with those of the Y(4660) supporting explanation that X(4630) $\equiv$ Y(4660) [60]. Among interpretations for the X(4630) are a conventional charmonium state [61], a baryon-antibaryon threshold effect [62], point-like baryons [63] and a tetraquark state [64].

4   The XYZ(3940) family

Curiously, four states were observed with similar masses near $3.91 - 3.94$ GeV/c^2, but in quite different processes (Table 2). The Z(3930) state found by Belle in two-photon collisions $\gamma\gamma \to D\overline{D}$ with a mass ~ 3.930 GeV/c^2 [5] and recently confirmed by BABAR [67] was identified as the $\chi_{c2}(2P)$ charmonium state.

The X(3940), has been observed by Belle in double charmonium production via the process $e^+e^- \to J/\psi D\overline{D}^*$ in the mass spectrum recoiling against the J/ψ [15] and confirmed in 2008 with a significance of 5.7σ [65]. In addition Belle found a new charmonium-like state, X(4160), decaying into $D^*\overline{D}^*$ with a signi-

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1) In PGD [30] this state is called the X(4260)

2) In PGD [30] this state is called the X(4360)

Table 2. Measured parameters of the XYZ(3940) states.

state	$M/(\,\mathrm{MeV}/c^2)$	$\Gamma_{\mathrm{tot}}/\mathrm{MeV}$	J^{PC}	decay	production	collaboration
X(3940)	$3942^{+7}_{-6}\pm6$	$37^{+26}_{-18}\pm8$	?$^?$+	$D\overline{D}^*$	$e^+e^- \to J/\psi X(3940)$	Belle 07 [65]
X(4160)	$4156^{+25}_{-20}\pm15$	$139^{+111}_{-61}\pm21$	?$^?$+	$D^*\overline{D}^*$	$e^+e^- \to J/\psi X(4160)$	Belle 07 [65]
Y(3940)	$3943\pm11\pm13$	$87\pm22\pm26$	?$^?$+	$\omega J/\psi$	$B \to KY(3940)$	Belle 05 [7]
Y(3940)	$3914.6^{+3.8}_{-3.4}\pm2.0$	$34^{+12}_{-8}\pm5$	?$^?$+	$\omega J/\psi$	$B \to KY(3940)$	BABAR 08 [66]
Z(3930)	$3929\pm5\pm2$	$29\pm10\pm2$	2^{++}	$D\overline{D}$	$\gamma\gamma \to Z(3940)$	Belle 05 [5]
X(3915)	$3915\pm3\pm2$	$17\pm10\pm3$	$0^{+?},2^{+?}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	Belle 09 [8]

ficance of 5.1σ in the processes $e^+e^- \to J/\psi X(4160)$. Both the X(3940) and the X(4160) decay to open charm final states and therefore could be attributed to 3^1S_0 and 4^1S_0 conventional charmonium states. However, potential models predict masses for these levels to be significantly higher than measured ones.

The Y(3940) state has been observed by Belle as a near-threshold enhancement in the $\omega J/\psi$ invariant mass distribution for exclusive $B \to K\omega J/\psi$ decays with a significance of 8.1σ [7]. BABAR has confirmed the Belle result in the decays $B^{0,+} \to K^{0,+}\omega J/\psi$ [66] and but obtained a lower mass $\sim 3.915\,\mathrm{GeV}/c^2$ and smaller width. The ratio of B^0 and B^+ decay to Y(3940)K, $R_Y = 0.27^{+0.28+0.04}_{-0.23-0.01}$, is found to be ~ 3 standard deviations below the isospin expectation, but agrees with that for the X(3872) [37].

The obtained upper limits: $\mathcal{B}(Y(3940) \to \omega J/\psi)/\mathcal{B}(Y(3940) \to D^0\overline{D}^{*0}) > 0.71$ at the 90% C.L. [15] and $\mathcal{B}(X(3940) \to \omega J/\psi)\mathcal{B}(X(3940) \to D^0\overline{D}^{*0}) < 0.58$ at the 90% C.L. [42], allow to claim that the X(3940) and the Y(3940) are different states.

This year Belle observed a significant (7.7σ) peak just above threshold near $\sim 3.915\,\mathrm{GeV}/c^2$ in two-photon collisions $\gamma\gamma \to \omega J/\psi$, called the X(3915) [8]. The X(3915) mass is $\sim 2\sigma$ lower than the Z(3930) mass but is in a good agreement with mass of the Y(3940) measured by BABAR. The same decay channel $\omega J/\psi$ and similar widths are two more arguments to claim that X(3915) $\equiv$ Y(3940).

5 New Y(4140) and X(4350) states

This year CDF reported evidence for a narrow structure near the $J/\psi\phi$ threshold in exclusive $B^+ \to J/\psi\phi K^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV [68]. Assuming an s-wave relativistic BW, the mass and width of the structure, called Y(4140), were measured to be $(4143.0\pm2.9\pm1.2)\,\mathrm{MeV}/c^2$ and $(11.7^{+8.3}_{-5.0}\pm3.7)$ MeV, respectively. As conventional charmonium with such mass is expected to decay into an open charm pair dominantly and to have a tiny branching fraction into $J/\psi\phi$, the Y(4140)[1], is a can-

didate to be exotic charmonium-like state.

The Belle collaboration has found no signal for the Y(4140) using the same process with 772×10^6 $B\overline{B}$ pairs [69]. However, the upper limit on the production rate $\mathcal{B}(B^+ \to Y(4140)K^+, Y(4140) \to J/\psi\phi)$ measured to be 6×10^{-6} at the 90% C.L. is not inconsistent with central value of the CDF measurement $(9.0\pm3.4\pm2.9)\times10^{-6}$.

Belle has not observed a Y(4140) signal in the two-photon process $\gamma\gamma \to J/\psi\phi$ as well [70]. Conservative upper limits on the product of the two-photon decay width and branching fraction of Y(4140) $\to J/\psi\phi$ are established at $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \to J/\psi\phi) < 40$ eV for $J^P = 0^+$, or < 5.9 eV for $J^P = 2^+$ at the 90% C.L. and are lower than calculated values of (176^{+137}_{-93}) eV for $J^{PC} = 0^{++}$ and (189^{+147}_{-100}) eV for $J^{PC} = 2^{++}$ [70].

In the same process in the $J/\psi\phi$ mass spectrum Belle has found an unexpected new narrow structure at 4.35 GeV/c^2 with a significance of 3.2σ [70]. If this structure, called Y(4350), is interpreted as a resonance, its mass and width are $(4350.6^{+4.6}_{-4.1}\pm0.7)\,\mathrm{MeV}/c^2$ and $(13.3^{+17.9}_{-9.1}\pm4.1)$ MeV, respectively. The product of its two-photon decay width and branching fraction to $J/\psi\phi$ is measured to be $\Gamma_{\gamma\gamma}(Y(4350))\mathcal{B}(Y(4350) \to J/\psi\phi) = (6.7^{+3.2}_{-2.4}\pm1.1)$ eV for $J^P = 0^+$, or $(1.5^{+0.7}_{-0.6}\pm0.3)$ eV for $J^P = 0^+$.

The statistical significances of both the Y(4140) and the X(4350) are less than 4σ and therefore these states need confirmation. We do not discuss here numerous interpretations of them.

6 The charmonumlike states with nonzero electric charge

In 2007 Belle reported an observation of the first candidate charmonium-like state with nonzero electric charge [9]. Such a state, if it exists, could only be a multiquark state and not conventional charmonium or a hybrid. A distinct peak, called the Z(4430)$^+$, was found in the $\pi^+\psi(2S)$ invariant mass distribution near $4.43\,\mathrm{GeV}/c^2$ in $B \to K\pi^+\psi(2S)$ decays with

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1) similar to the Y(3940), which decays to $\omega J/\psi$ near threshold

Table 3. Measured parameters of the $Z^\pm$ states.

state	$M/(\,\mathrm{MeV}/c^2)$	$\Gamma_\mathrm{tot}/\,\mathrm{MeV}$	J^{PC}	decay modes	production	collaboration
$Z(4430)^+$	$4433\pm4\pm2$	45^{+18+30}_{-13-13}	?$^{??}$	$\pi^+\psi(2S)$	$\mathrm{B}\to\mathrm{K}Z^\pm(4430)$	Belle 07 [9]
$Z(4430)^+$	4443^{+15+19}_{-12-13}	107^{+86+74}_{-43-56}	?$^{??}$	$\pi^+\psi(2S)$	$\mathrm{B}\to\mathrm{K}Z^\pm(4430)$	Belle 09 [72]
$Z(4050)^+$	$4051\pm14^{+20}_{-41}$	82^{+21+47}_{-17-22}	?$^{??}$	$\pi^+\chi_{c1}$	$\mathrm{B}\to\mathrm{K}Z(4050)^+$	Belle 08 [10]
$Z(4250)^+$	$4248^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	?$^{??}$	$\pi^+\chi_{c1}$	$\mathrm{B}\to\mathrm{K}Z(4250)^+$	Belle 08 [10]

a statistical significance of 6.5σ. A fit using a Breit-Wigner resonance shape yields a peak mass and width presented in Table 3. The product branching fraction is determined to be $\mathcal{B}(\mathrm{B}\to\mathrm{K}Z(4430)^+)\times \mathcal{B}(Z(4430)^+\to\pi^+\psi(2S))=(4.1\pm1.0\pm1.4)\times10^{-5}$.

In 2008 BABAR presented a search for $Z(4430)^-\to\mathrm{J}/\psi\pi^-$ and $Z(4430)^-\to\psi(2S)\pi^-$ in $\mathrm{B}\to\mathrm{K}\pi^-\mathrm{J}/\psi(\psi(2S))$ decays, where $\mathrm{K}=\mathrm{K}^0_\mathrm{S}$ or K^+ [71]. BABAR performed a detailed study of $\mathrm{K}\pi^-$ reflections into the $\mathrm{J}/\psi\pi^-$ and $\psi(2S)\pi^-$ masses (in S-, P-, D-waves) to describe background for both J/ψ and $\psi(2S)$ modes. From the fits to $\mathrm{J}/\psi\pi^-$ mass distribution, in which background shape was fixed and s-wave Breit-Wigner was used as signal function, no evidence for any enhancement for J/ψ samples was found. From a similar fit for $\psi(2S)$ data, small signals with significance less than 3σ were obtained. BABAR claimed no significant evidence for existence of the $Z(4430)^-$.

This year Belle performed a Dalitz plot analysis of $\mathrm{B}\to\mathrm{K}\pi^+\psi(2S)$ decays [72] using the same data sample reported in Ref. [9]. The obtained mass and width of the signal (Table 3) and product branching fraction $\mathcal{B}(\mathrm{B}\to\mathrm{K}Z(4430)^+)\times\mathcal{B}(Z(4430)^+\to\pi^+\psi(2S))= (3.2^{+1.8+5.3}_{-0.9-1.6})\times10^{-5}$ agree with previous Belle measurements. The statistical significance of the $Z(4430)^+$ is 6.4σ (including systematic uncertainty from the fit models reduces this to 5.4σ).

Two more resonance-like structures were observed by Belle in the $\pi^+\chi_{c1}$ invariant mass distribution near

4.1 GeV/c^2 in exclusive $\overline{\mathrm{B}}^0\to\mathrm{K}^-\pi^+\chi_{c1}$ decays [10]. From a Dalitz plot analysis in which the $\pi^+\chi_{c1}$ mass structures are represented by Breit-Wigner resonance amplitudes, Belle determined masses and widths of these new structures (Table 3) and product branching fractions of $\mathcal{B}(\overline{\mathrm{B}}^0\to\mathrm{K}^-Z^+_{1,2})\times\mathcal{B}(Z^+_{1,2}\to\pi^+\chi_{c1})= (3.0^{+1.5+3.7}_{-0.8-1.6})\times10^{-5}$ and $(4.0^{+2.3+19.7}_{-0.9-0.5})\times10^{-5}$, respectively. The significance of each of the $\pi^+\chi_{c1}$ structures exceeds 5σ, including the effects of systematics from various fit models.

7   Conclusion

The discovery of numerous charmonium-like states discussed in this review became possible due to the excellent performance of both the KEKB and PEPII B-factories. Surprisingly, the major fraction of the observed charmonium-like states with masses above open charm threshold cannot be explained as conventional charmonium. Although the number of exotic theoretical interpretations of these states is growing, they can still not explain all of the existing observations. More efforts are needed both to improve the theoretical understanding and to perform more precise measurements of exotic states at Super B-factories.

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