Recent results from Belle

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Abstract

The review on experimental results on charmonium and charmonium-like spectroscopy from B-factories is presented. Main theoretical interpretations, such as conventional charmonium, molecular state, hybrids, tetraquarks and others are discussed.

1 Introduction

Operation of two B-factories, Belle [1] and BaBar [2], is likely the most significant success in the experimental particle physics of the last decade. Their brilliant work on CP-violation studies in B-mesons leads to Nobel Prize winning by Kobayashi and Maskawa. In addition to the CPV studies B-factories also made a huge contribution to the hadron spectroscopy, τ-, charm and two-photon physics. One of the most prominent discovery made by the B-factories is the observation of new charmonium-like states, so called X, Y and Z mesons. In this paper an experimental review of these states discovery and studies at B-factories is presented, principal theoretical theoretical interpretations are discussed.

2 The Belle detector

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). Two inner detector configurations were used. A beampipe at radius 2.0 cm and a 3-layer silicon vertex detector were used for the first sample of $\sim 156 fb^{-1}$, while a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining data sample of $\sim 800 fb^{-1}$.

3 Charmonium: a long story

The charmed particles are known already more than for 35 years. The first state, J/ψ was observed by Ting and Richter [3] in 1974, ten years after the c-quark theoretical prediction. There was a great progress in charmonium spectroscopy during next 6 years. Another 9 $(c\bar{c})$ states shown in Fig 1 were discovered: $\psi(2S)$ η_c, χ_{c0}, χ_{c1}, χ_{c2}, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$. Between 1980 and 2002 not a single new charmonium state was observed. The beginning of the new charmonium boom coincides with start of the B-factories operation.

There are several processes of charmonium production at the B-factories:

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1. production in B meson decays;
2. production in e^+e^- annihilation through ISR photon;
3. double charmonium production in e^+e^- annihilation;
4. production in two photon collisions.

Some of these mechanisms allow to fix quantum numbers of the final states. All charmonium states produced in e^+e^- annihilation have photon quantum numbers $J^{PC} = 1^{--}$; $(c\bar{c})$ pairs from the double charmonium production have opposite C-parities. Two photon production fix $C = +1$ and forbids $J = 1$.

Most of more than ten new charmonium-like states discovered at B-factories do not fit the conventional charmonium spectroscopy scheme. Observation of charmonium-like states with forbidden quantum numbers, charged or extremely narrow width is the direct evidence of the non-conventional spectroscopy. Thus the studies of the new states could lead to the new revolution in the hadron physics.

4 X(3872)

The first and may be the most mysterious charmonium-like particle, $X(3872)$, was found by Belle collaboration in 2003 [4] in $B^+ \to J/\psi\pi^+\pi^- K^+$ exclusive decay. Except for well-known $\psi(2S)$ resonance, a new peak of more than 10σ significance at mass $(3872.0 \pm 0.6 \pm 0.5)\,\mathrm{MeV}/c^2$ was found in the $J/\psi\pi^+\pi^-$ mass spectrum. Mass of the new state and presence of $(c\bar{c})$ pair in the decay products indicated charmonium nature of $X(3872)$. However it's compatible with zero width ($\Gamma_{tot} < 2.3\,\mathrm{MeV}$ @ $90\,\%\,CL$) as well as mass equal within errors to the sum of D^{*0} and D^0 mesons rise doubts on this interpretation. Until now it is unknown whether the mass of $X(3872)$ is above or below $D^0 D^{*0}$ threshold: $\Delta m = -0.25 \pm 0.40\,\mathrm{MeV}/c^2$. An existence and properties of $X(3872)$ was confirmed by CD, D0 and BaBar collaborations [5].

So narrow width for the state $\sim 138\,\mathrm{MeV}$ above the $D\overline{D}$ threshold and absence of $X(3872) \to D\overline{D}$ decay ($\Gamma(X \to D\overline{D})/\Gamma(X \to J/\psi\pi^+\pi^-) < 7$ @ $90\%\,CL$ [6]) means that the latter is forbidden either by parity conservation (if $X(3872)$ has unnatural spin-parity $J^P = 0^-, 1^+, 2^-, \dots$) or high orbital momentum, *e.g.* $J^P = 3^-, 4^+, \dots$ Presence of gluon or pair of the light quarks except for $(c\bar{c})$ pair in $X(3872)$ could also leads to suppression.

Observed enhancement at higher mass region in $m(\pi^+\pi^-)$ spectrum could be interpreted as $X \to J/\psi\rho^0$ decay [7]. Since charmonium decay to $J/\psi\rho^0$ violates isospin symmetry observation of this decay would be a strong argument against charmonium nature of $X(3872)$ state. First evidence of $X(3872)$ radiative decays was reported by Belle in 2005 [8] and confirmed by BaBar collaboration in 2009 [9]. Decay $X(3872) \to J/\psi\gamma$ was observed with signal significance above 3.5σ, thus fixing $C(X) = +1$. Positive charge parity of X supports hypothesis of $J/\psi\rho^0$ decay.

Direct quantum numbers measurements are possible with angular analysis. Performed by the Belle collaboration [7] it excludes $J^{PC} = 0^{++}$ and 0^{+-} possibilities. More accurate analysis done by CDF [10] excludes all J^{PC} for $J \leq 3$, except for 1^{++} and 2^{-+}. Recent BaBar studies [11] of $X(3872) \to J/\psi\omega$ decay insignificantly favours negative parity assignment.

5 Y(3940)

Another puzzling state, $Y(3940)$, was found by Belle collaboration [12] in $B^+ \to J/\psi\omega K^+$ decays. Near-threshold event excess in $J/\psi\omega$ spectrum was interpreted as positive parity resonance of mass $(3943 \pm 11 \pm 13)\,\mathrm{MeV}/c^2$ and width $(87 \pm 22 \pm 26)\,\mathrm{MeV}$. Three years later this state was confirmed by BaBar [13], however measured resonance mass and width, $(3914.6 \pm 2 \pm 1.9)\,\mathrm{MeV}/c^2$ and width $(34^{+12}_{-8} \pm 6)\,\mathrm{MeV}$, respectively, differs from previously

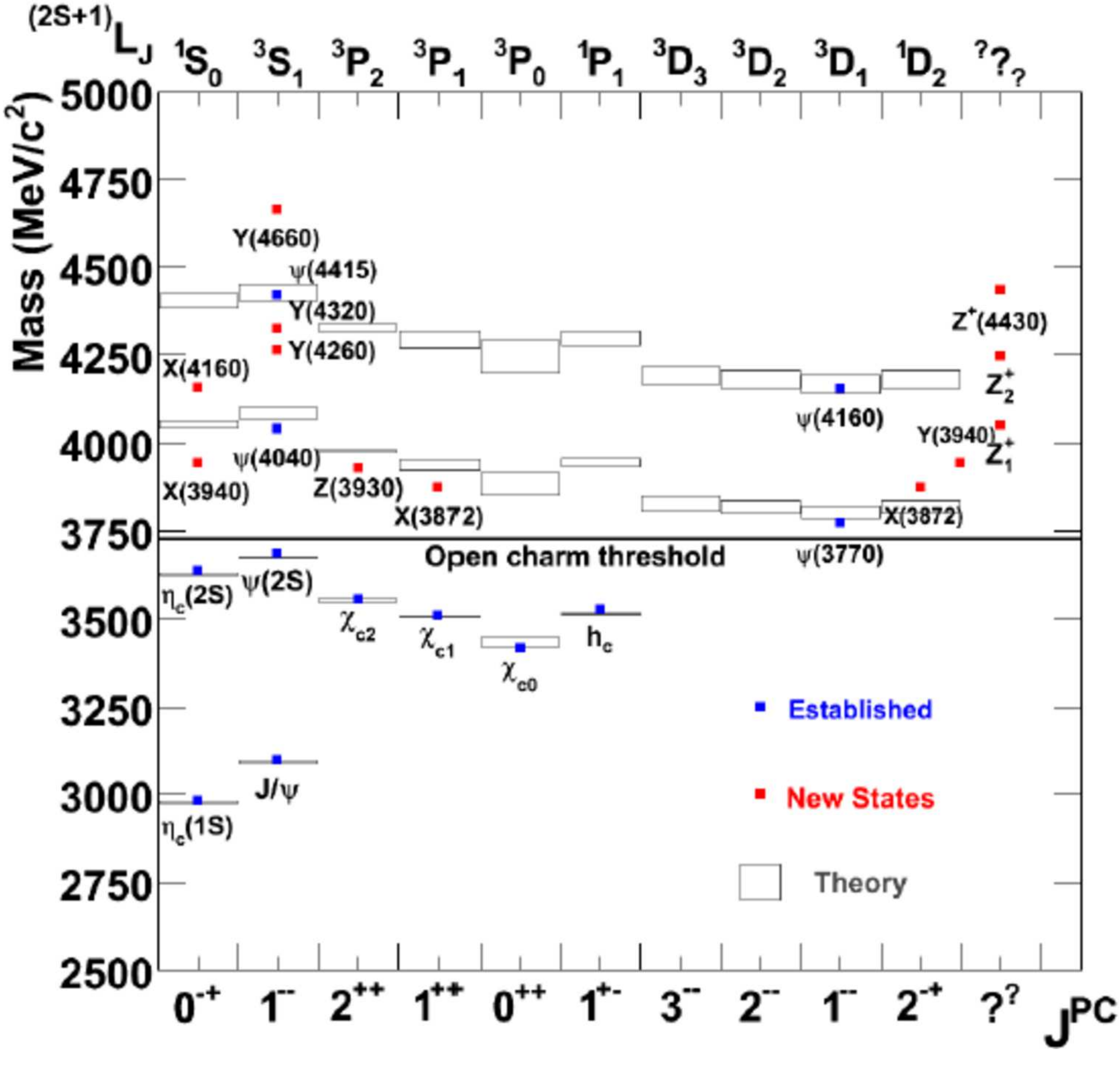

Figure 1: Charmonium spectroscopy.

reported by Belle. Signal was found both for the charged and neutral B meson decays with surprising ratio for this two channels $N(B^{\pm})/N(B^0) = 0.27^{+0.28}_{-0.23}$, about 3σ below predictions based on isospin symmetry. Observation of two-photon Y production [14] with mass and width similar to the BaBar values fix J_Y to 0 or 2. Quantum numbers of Y could be determined via angular analysis. These results will clear up the nature of the resonance.

6 Charmonium-like states in double charmonium production

Double charmonium production is another source of charmonium-like states. Studying recoil mass spectrum against J/ψ, Belle collaboration found [15], among known charmonium states, η_c, χ_{c0} and $\eta_c(2S)$, another narrow with respect to the resolution $\Gamma_{tot} < 52\,\mathrm{MeV}\,@\,90\%\,CL$ peak of at mass $(3943 \pm 6 \pm 6)\,\mathrm{MeV}/c^2$. The discovery was soon confirmed by exclusive process reconstruction in $e^+e^- \to J/\psi D\overline{D}^*$ channel [16]. Studies of similar final state $J/\psi D^*\overline{D}^*$ leads to discovery of another narrow state of width of $(139^{+111}_{-61} \pm 21)\,\mathrm{MeV}$ with mass $(4156^{+25}_{-20})\,\mathrm{MeV}/c^2$ decaying to $D^*\overline{D}^*$. Although mass and width of new $X(4160)$ resonance agrees with those of known $\psi(4160)$ charmonium state, charge parity, fixed by their production mechanisms, is opposite.

7 J/$\psi\varphi$ resonances: Y(4140) & Y(4350)

Last year CDF reported evidence for the new narrow state [17] with mass of $4143.0 \pm 2.9 \pm 1.2\,\mathrm{MeV}/c^2$ and width $11.7^{+0.83}_{-5.0} \pm 3.7\,\mathrm{MeV}$. New resonance of 3.8σ significance was observed in $B \to J/\psi\varphi K$ decays of B mesons produced in $p\bar{p}$ at $\sqrt{s} \sim 1.96\,\mathrm{TeV}$. Belle collaboration does not confirm this peak [18], however low efficiency near the threshold disallows to report the contradiction. Search for this state in $\gamma\gamma$ collisions also fails [19]. At the same time a new narrow structure $J/\psi\varphi$ mass spectrum of 3.2σ significance was observed at $4.35\,\mathrm{GeV}/c^2$. Being interpreted as resonance, this structure has mass and width of $(4350.0^{+4.6}_{-4.1} \pm 0.7\,\mathrm{MeV}/c^2)$ and $(13.3^{+17.9}_{-9.1} \pm 4.1\,\mathrm{MeV})$, respectively. The significance of both $Y(4140)$ and $Y(4350)$ states are less than 4σ, thus their confirmation is required.

8 ISR family: Y(4008), Y(4260), Y(4350) and Y(4660)

First state of this family was discovered in 2005. Inspired by $X(3940)$ observation, BaBar collaboration undertake a search [23] for the resonance in $J/\psi\pi^-\pi^+$ spectrum in the $e^+e^- \to J/\psi\pi^-\pi^+\gamma_{ISR}$ process. A clear peak with mass and width of $(4264 \pm 12\,\mathrm{MeV}/c^2)$ and $(83 \pm 22)\,\mathrm{MeV}$, respectively, was found. Similar analysis done by Belle confirms $Y(4260)$, besides them another structure at mass of $(4008 \pm 40^{+114}_{-28})\,\mathrm{MeV}/c^2$ and width of $(226 \pm 44 \pm 87)\,\mathrm{MeV}$ was found. Fit of the mass distribution with two interfering Brait-Wigner shapes results in unavoidable splitting: there are two solution of the same significance, resonance masses and widths, but with different amplitudes.

In 2007 repeating the analysis for $\psi(2S)\pi^+\pi^-\gamma_{ISR}$ final state [20] BaBar found an evidence for a new resonance decaying to $\psi(2S)\pi^+\pi^-$. Belle confirms [21] this peak and found another one at higher mass. The masses and widths of new $Y(4350)$ and $Y(4660)$ states were determined to be $M = 4355^{+9}_{-10} \pm 9\,\mathrm{MeV}/c^2$, $\Gamma = 103^{+17}_{-15} \pm 11\,\mathrm{MeV}$ and $M = 4661^{+9}_{-8} \pm 6\,\mathrm{MeV}/c^2$, $\Gamma = 47^{+17}_{-12}\,\mathrm{MeV}$, respectively. The latter states was also found in $\Lambda_c\overline{\Lambda}_c$ mass spectrum in $e^+e^- \to \Lambda_c\overline{\Lambda}_c\gamma_{ISR}$ process [22].

9 Z: charged charmonium?

Probably the most speculating charmonium-like states are those of Z-family. The first evidence for charged charmonium-like state was found by Belle in 2008 [24]. Studying $\psi(2S)\pi^+$ mass spectrum for $B \to \psi(2S)\pi^+K$ decay after discarding $B \to \psi(2S)K^*$ events a narrow structure of 6.5σ significance near $4.43\,\mathrm{GeV}/c^2$ was found. Fit to this distribution returns mass and width of the new $Z^+(4430)$ resonance of $(4433 \pm 4 \pm 2)\,\mathrm{MeV}/c^2$ and $(45^{+18+30}_{-13-13})\,\mathrm{MeV}$, respectively. Next year same data were analysed using more sophisticated technique [25]. Fit to the Dalitz distribution $M^2(\psi(2S)\pi^+)\,vs.\,M^2(K\pi^+)$ results in similar Z's mass and slightly higher width of $(107^{+86+74}_{-43-56})\,\mathrm{MeV}$. However, no significant signal of $Z(4430)$ was found by the BaBar collaboration [26]: only the upper limit have been set $\mathcal{B}(B \to Z^+K)\cdot\mathcal{B}(Z^+ \to \psi(2S)\pi^+) < 3.1\cdot 10^{-5}$, which is lower than measured by Belle $(4.1 \pm 0.1 \pm 1.4)\cdot 10^{-5}$. Search for Z's in $B \to \chi_{c1}\pi^+K$ process turns out even more puzzling. Dalitz plot fit to broad structure in $\chi_{c1}\pi^+$ mass results in two charged charmonium-like resonances with masses of $(4051 \pm 14^{+20}_{-41}\,\mathrm{MeV}/c^2)$ and $(4248^{+44+180}_{-29-25})\,\mathrm{MeV}/c^2$, and widths of $(82^{+21+47}_{-17-22})\,\mathrm{MeV}/c^2$ and $(177^{+54+316}_{-39-61})\,\mathrm{MeV}$, respectively. A hypothesis of two resonance is $\sim 5.7\sigma$ more preferable in respect with one Z.

10 New states: interpretation

There are several general interpretations of the new charmonium-like states are now under discussion. Their current theoretical and experimental status is summarized in Table 1.

State	M, MeV/c^2	Γ, MeV	J^{PS}	Possible interpretation
$X(3872)$	3871.4 ± 0.6	< 2.3	2^{-+}	Molecule, χ'_{c1}, $\eta_c(2S)$, tetraquark
$X(3915)^\dagger$	3914 ± 4	23 ± 9	$0/2^{++}$	$Y(3940)$
$Z(3930)^\dagger$	3929 ± 5	29 ± 10	2^{++}	$\chi_c(2P)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{+?}$	$\eta_c(3S)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	Conventional $(c\bar{c})$, hybrid
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	non-res $J/\psi\pi^+\pi^-$
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$\eta_c(4S)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	3^3D_1
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	Molecule,tetraquark, hadrocharmonium, hybrid
$X(4630)^\dagger$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$Y(4660)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	Molecule,tetraquark, hadrocharmonium, hybrid
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	Molecule,tetraquark, hadrocharmonium, hybrid
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	Molecule,tetraquark, hadrocharmonium, hybrid
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	Molecule,tetraquark, hadrocharmonium, hybrid

Table 1: Charmonium-like states and their interpretation. Only states shown with † sign are well interpreted.

- *Conventional charmonium* is the most well known and the only experimentally proved model tuned to describe charmonium below the $D\overline{D}$ threshold. It constrains quantum numbers of the state: $J = L + S; P = (-1)^{L+1}; C = (-1)^{L+S}$.

  In conventional charmonium model $X(3872)$ state could be interpreted as χ'_{c1}. However the measured decay rate $\mathcal{B}(X \to J/\psi\gamma)/\mathcal{B}(X \to J/\psi\pi\pi) < 0.2$ is much smaller than predicted (~ 30). Possible $X(3872)$ treatment as $\eta_c(2S)$ expects large $\Gamma(X \to gg)$ and tiny $\Gamma(X \to J/\psi\pi\pi)$ which contradicts to the experiment.

  Interpretation of $Y(3940)$ as conventional charmonium also faced the problems. Assuming that probability of $B \to Y(3940)K$ decay is less than 10^{-3}, which is usual for $B \to (c\bar{c})K$; $(c\bar{c}) = \eta_c, J/\psi, \chi_{c0}, \chi_{c1}, \psi(2S)$ decays, one could calculate $\Gamma(Y(3940) \to J/\psi\omega) \sim 1\,\text{MeV}$, which is mote than 10 times large than for known charmonium transitions. Absence of $D\overline{D}$ and $D^*\overline{D}$ decays is also counts against charmonium interpretation.

  A lack of $D^{(*)}\overline{D}^{(*)}$ decays also prevents to the $Y(4260)$ interpretation as conventional 3^3D_1 $(c\bar{c})$ state.

  For $X(3940)$ and $X(4160)$, candidates for 3^1S_0 and 4^1S_0 states, respectively, the discrepancies between the predicted and measured masses reach $\sim 100\,\text{MeV}/c^2$ and $\sim 250\,\text{MeV}/c^2$, respectively.

  For two states observed in ISR, $Y(4360)$ and $Y(4660)$ there are no vacant 1^{--} states in the conventional charmonium spectroscopy scheme and they are too broad for it.

- *Molecular state* is two mesons loosely bounded by pion or gluon exchange.

  Molecule is the most popular interpretation of $X(3940)$. Belief that fine coincidence between X's mass and $D^*\overline{D}$ threshold is not accidental, observed decays to $D^*\overline{D}$ and a tiny radiative decay to J/ψ rate strongly supports molecular hypothesis. *Contra* arguments are too large $X \to \psi(2S)\gamma$ decay width and too small binding energy: D mesons are too far from each other to be produced in $p\bar{p}$ collisions as an entity. However a possibility to mix with χ'_{c1} state solves all these problems.

No evidence for $Y(4140)$ production in two-photon collisions is found for now. Small $\gamma\gamma$ width disfavours its molecular interpretation.

Molecule composed of $D\overline{D}_1$ or $D_0\overline{D}^*$ is a good hypothesis for $X(3940)$ and $X(4160)$ states.

Charged Z's could be treated as $D^{(*)}_{(s)}\overline{D}^{(*)}_{(s)}$ molecule.

- *Tetraquark* is tightly bound four quark state.

  Tetraquark interpretation predicts a list of new states with small mass spiting, especially for $(c\bar{u})(\bar{c}u)$, $(c\bar{d})(\bar{c}d)$ and $(c\bar{u})(\bar{c}d)$ combinations. Intensive searches for $X(3872)$ find no evidence neither for charges nor for neutral partners.

  Some resonances from Y family, $Y(4360)$ and $Y(4660)$ could be treated as $(\bar{c}q)(c\bar{q})$ tetraquark, $Y(4140)$ and $Y(4350)$ as $(s\bar{s}c\bar{c})$ diquark-antidiquark state. For Z's there is $(c\bar{q}_1)(\bar{c}q_2)$ interpretation.

- *Hybrid* — meson with excited gluon degree of freedom. Interpretations of $Y(4360)$ and $Y(4660)$ states as hybrids is supported by lattice calculations, however in such a model, contrary to experiment, $D^{(*)}D^{**}$ decays should dominate.

- *Hadrocharmonium* — charmonium coated by excited hadronic matter. $Y(4360)$ and $Y(4660)$ could be treated as $(c\bar{c})$and excited light meson hadrocharmonium. Excited charged light meson coating $\psi(2S)$ or χ_{c1} could give Z's.

- There are discussion on dynamical nature of new states. *Threshold effects* caused by virtual states near the threshold could be responsible for these structures.

11 Conclusions: a challenge

Results of B-factories, Belle and BaBar, Tevatron experiments (CDF, D0) as well as many others (BES etc.) start a new exciting era in the hadron spectroscopy. Seven years passed after discovery of $X(3872)$, first charmonium-like state. More than ten another puzzling structures were observed since that time and only a tiny fraction of them are interpreted for now. New hadronic 'zoo' is a great challenge for theoreticians to explain the nature of these states and for experimentalist to measure their properties with a highest possible precision. New data from the upcoming Super-B-factories [27] would illuminate the mystery of this charmonium-like family and hopefully solve XYZ puzzle.

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