PROCEEDINGS OF SCIENCE

Charmonium Spectroscopy (X,Y,Z) at the B Factories

Michal Kreps[*†]
Karlsruhe Institute for Technology
E-mail: michal.kreps@kit.edu

Since 2003 several states in the charmonium mass region were discovered. While in the conventional $c\bar{c}$ spectrum some states are missing, the number of states observed up to now is larger than empty spaces in the $c\bar{c}$ spectrum. This, together with other difficulties to explain observed states as a $c\bar{c}$ mesons triggered discussions on a possible exotic interpretations. In this proceedings we present current experimental status from B-factories of the so called X, Y and Z states.

12th International Conference on B-Physics at Hadron Machines - BEAUTY 2009
September 07 - 11 2009
Heidelberg, Germany

[*]Speaker.
[†]On behalf of the Belle and *BABAR* collaborations.

PoS(BEAUTY 2009)038

1. Introduction

The charmonium ($c\overline{c}$) spectrum is thought to be well understood with a good agreement between theory and experiment. With current generation of B-factories also search for an unobserved but predicted states began. First state was observed in 2003 by Belle experiment [1] and is known now as $X(3872)$. In a following years, many other states were observed. Very quickly it become clear that those states are difficult to explain as conventional $c\overline{c}$ mesons given our understanding of the $c\overline{c}$ spectra. All those mesons have in common a mass in charmonium region and a rather narrow width. While being above the threshold for a decay to a pair of open charm mesons, they were observed in the decays containing J/ψ in a final state. The states are named X, Y and Z which reflects the unknown nature of them.

The difficulty in fitting observed status to the charmonium spectrum in connection with few other properties discussed later triggered speculations that at least some of the observed states might be candidates for exotic mesons. Those include variety of options like molecule of two loosely bound mesons, different variations of four quark states, hybrids or glueballs. In this write-up we present the current status and developments in experimental studies of the X, Y and Z mesons at B-factories experiments Belle and *BABAR*.

2. The $X(3872)$

The $X(3872)$ is best known and studied out of the puzzling XYZ states. It was observed in 2003 in the B^+ decays to $X(3872)K^+$ with $X(3872)$ decaying to $J/\psi\pi^+\pi^-$ [1]. The state was subsequently confirmed in B decays by *BABAR* experiment [2] and in $p\overline{p}$ production by Tevatron experiments CDF [3] and DØ [4]. Already first measurements yielded mass in the proximity of $D^0\overline{D}^{*0}$ threshold. From the subsequent observation of decays $X(3872) \to J/\psi\gamma$ [5] and the angular analysis performed by CDF experiment [6], the possible quantum numbers were reduced to two options of $J^{PC} = 1^{++}$ or 2^{-+}. In addition, decays to $D^0\overline{D}^{*0}$ were observed [7, 8], but the mass measured in this decay mode was about 3 MeV above the mass measured in the $J/\psi\pi^+\pi^-$ decay.

Several new measurements were performed in the past year by both B-factory experiments. Using 657 million $B\overline{B}$ pairs, Belle experiment updated the mass measurement in the $J/\psi\pi^+\pi^-$ final states [9]. Combining $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K_s$ samples together they measure $M(X(3872)) = 3871.46 \pm 0.37 \pm 0.07$ MeV$/c^2$. The difference of the masses measured separately in B^+ and B^0 decays is $\delta M = 0.18 \pm 0.89 \pm 0.26$ MeV$/c^2$. The analogous result from *BABAR* experiment based on the 455 million $B\overline{B}$ pairs gives $M(X(3872)) = 3871.4 \pm 0.6 \pm 0.1$ MeV$/c^2$ and $\delta M = 2.7 \pm 1.6 \pm 0.4$ MeV$/c^2$ [10]. In both cases, the measured mass of the $X(3872)$ is slightly below $D^0\overline{D}^{*0}$ threshold, but mass above the $D^0\overline{D}^{*0}$ threshold cannot be excluded. The updated study of Belle collaboration adds in addition first observation of the $X(3872)$ in the $B^0 \to X(3872)K^+\pi^-$ decay. In Fig. 1 we show $J/\psi\pi^+\pi^-$ and $K^+\pi^-$ invariant mass distributions. The fit of the $K^+\pi^-$ mass distribution including possibility of resonant decays $B^0 \to X(3872)K^{*0}$ as well as non-resonant $B^0 \to X(3872)K^+\pi^-$ reveals that most of the $X(3872)$ signal comes from the non-resonant B decays. The measured yields lead to $\mathscr{B}(B \to X(K\pi)_{non-res}) \cdot (X \to J/\psi\pi\pi) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$ and $\mathscr{B}(B \to XK^*) \cdot (X \to J/\psi\pi\pi) < 3.4 \times 10^{-6}$ at 90% C.L. The ratio between two B decays is opposite to the one seen in a case of well known conventional $c\overline{c}$ states

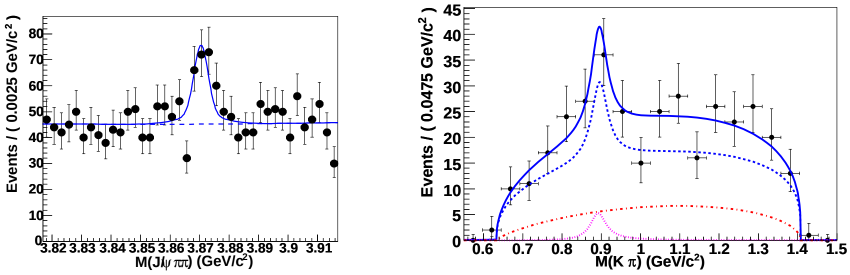

Figure 1: The $J/\psi\pi^+\pi^-$ invariant mass distribution (left) and $K^+\pi^-$ invariant mass distribution (right) for $B^0 \to J/\psi\pi^+\pi^-K^+\pi^-$ from Belle. In the $K^+\pi^-$ distribution only events in $X(3872)$ region are used. The full line shows the fit projection, the dashed blue line represents background, the dashed-dotted shows non-resonant decays with $X(3872)$ signal and the dotted curve shows resonance decays with $X(3872)$ signal.

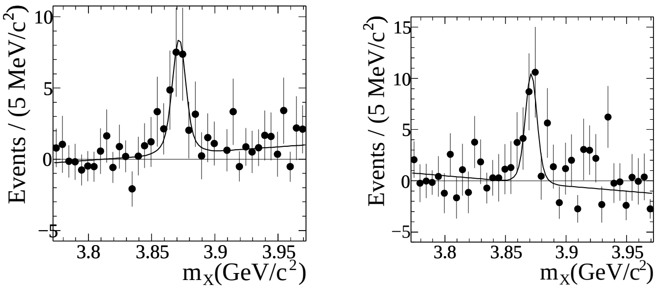

Figure 2: The $J/\psi\gamma$ (left) and $\psi(2S)\gamma$ (right) invariant mass distribution of B^+ signal events from *BABAR* experiment.

where the resonant decay through K^* is dominant over the non-resonant $K^+\pi^-$ and adds another puzzle to the nature of $X(3872)$.

A second important update concerns decays of the $X(3872)$ into $D^0\overline{D}^{*0}$ final state. The measured mass in this final state is one of the driving points of a four-quark hypothesis. On the other hand, measuring mass in this decay mode is a non-trivial task due to the proximity of kinematical threshold. The Belle experiment provided update, using 657 million $B\overline{B}$ pairs [11] to measure mass of $M = 3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV$/c^2$. Corresponding older measurement from *BABAR* experiment yields the mass $M = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV$/c^2$ [8]. It is worth to note that the new Belle mass measurements are compatible between $J/\psi\pi^+\pi^-$ and $D^0\overline{D}^{*0}$ decay modes. While a tetraquark interpretation cannot be excluded based on these measurements, the new mass measurement in the $D^0\overline{D}^{*0}$ and small δM in the $X(3872) \to J/\psi\pi^+\pi^-$ decay mode disfavor particular model of Maiani et al [12].

A third measurement to mention is the search for radiative decays of the $X(3872)$ to charmonium states. The *BABAR* experiment presented recent study of decays $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi(2S)\gamma$ using their full dataset [13]. An observation of radiative decays will fix charge parity on one hand and a pattern of branching fractions to different $c\overline{c}$ states can distinguish different interpretations on the other hand. While $D^0\overline{D}^{*0}$ molecule hypothesis can accommodate decays to the $J/\psi\gamma$, decays to the $\psi(2S)\gamma$ are expected to be very small in such a case. The obtained $J/\psi\gamma$ and $\psi(2S)\gamma$ invariant mass distributions are shown in Fig. 2. Both decay modes show evidence

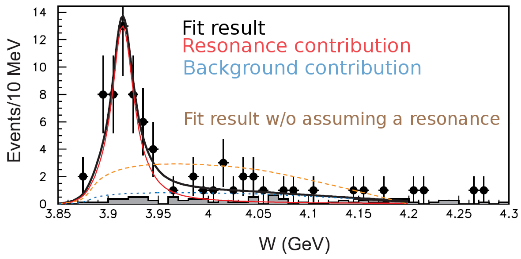

Figure 3: The number of $J/\psi\omega$ events as a function of $\gamma\gamma$ center of mass energy from Belle experiment.

for a signal with a significance of about 3.5σ. The ratio of branching fractions is measured to be $\mathscr{B}(X(3872) \to \psi(2S)\gamma)/\mathscr{B}(X \to J/\psi\gamma) = 3.4 \pm 1.4$, which indicates that even if the $X(3872)$ is a $D^0\overline{D}^{*0}$ molecule, it has a significant $c\bar{c}$ component.

3. States around 3940 MeV

A second area with recent result concerns states seen in the $J/\psi\omega$ final state with masses around 3940 MeV$/c^2$. History of this region goes back to 2005, when Belle using B decays observed a signal close to the $J/\psi\omega$ threshold [14]. The measured resonance parameters are $M = 3943 \pm 11 \pm 13$ MeV$/c^2$ and $\Gamma = 87 \pm 22 \pm 26$ MeV$/c^2$. Later the signal was confirmed by *BABAR* experiment, again in B decays with parameters $M = 3914.3^{+3.8}_{-3.4} \pm 2.0$ MeV$/c^2$ and $\Gamma = 34^{+12}_{-8} \pm 5.0$ MeV$/c^2$ [15]. Recently, Belle experiment a performed study of the $J/\psi\omega$ final state in the $\gamma\gamma$ fusion. The preliminary invariant mass distribution is shown in Fig. 3. A clear signal with $55 \pm 14^{+2}_{-14}$ events and a significance of 7.7σ is observed. The fit returns $M = 3914 \pm 3 \pm 2$ MeV$/c^2$ and $\Gamma = 23 \pm 10^{+2}_{-8}$ MeV$/c^2$. It is currently unclear, whether three signals seen in the $J/\psi\omega$ final state are due to single resonance or not. Additionally it is also unclear whether we see a new exotic state, or whether at least some of the peaks are actually different decay mode of the conventional $c\bar{c}$ state χ'_{c2}.

4. The 1^{--} Y family

Next puzzling area consist of four states observed in the ISR production and decaying to the $J/\psi\pi\pi$ or $\psi(2S)\pi\pi$ [16]. The four observed states are named Y. The masses of the two states seen in $J/\psi\pi\pi$ are about 4008 and 4250 MeV$/c^2$ and those seen in the $\psi(2S)\pi\pi$ final state about 4360 and 4660 MeV$/c^2$. The widths of the states are about 100 MeV$/c^2$ with narrowest one being 48 MeV$/c^2$. The *BABAR* experiment presented a recent update of the measurement in $e^+e^- \to J/\psi\pi\pi\gamma_{ISR}$. The updated values of the resonance parameters of $Y(4260)$ are $M = 4252 \pm 6\ ^{+2}_{-3}$ MeV$/c^2$ and $\Gamma = 105 \pm 18^{+4}_{-6}$ MeV$/c^2$. It should be noted, that *BABAR* experiment observes only $Y(4260)$ and $Y(4360)$ states without convincing signal for the other two. While for the $Y(4008)$ even Belle signal is not very convincing, for $Y(4660)$ the Belle signal is very clear. Also *BABAR* experiment sees a small enhancement around 4660 MeV$/c^2$ in $\psi(2S)\pi\pi$ final state, which can be interpreted as resonance whose parameters are consistent with Belle result, but the excess does not pass 3σ significance. Also search in the open charm meson pairs was performed. The Belle experiment studied DD final state [17] while new *BABAR* experiment measures three different $D^{(*)}D^{(*)}$ final states [18]. In both cases, none of the Y states can be identified with a clear signal in the mass distributions of $D^{(*)}D^{(*)}$ pairs.

The four states discussed here have $J^{PC} = 1^{--}$ which is fixed by the production mechanism in which they are observed. There seems to be no evidence for a decay to open charm mesons as expected for a conventional $c\bar{c}$ states above the open charm threshold. If all four states will be confirmed with higher statistics experiment, then it will be difficult to accommodate all of them into convention charmonium spectrum as there are not enough unobserved states available.

5. Resonances in $J/\psi\phi$

All XYZ states observed so far decayed to final states which does not contain strange quarks. The situation changed early this year, when CDF collaboration using $B^+ \to J/\psi\phi K^+$ decays published evidence for a near threshold resonance in the $J/\psi\phi$ channel, which was named $Y(4140)$ [19]. Using events within ± 3 resolutions around the B^+ mass, which contains 75 ± 10 B^+ signal events on a low combinatorial background, they extract 14 ± 5 signal events in the narrow $J/\psi\phi$ resonance. Fit with relativistic s-wave Breit-Wigner function for the signal, three body phase space for the background returns $M = 4143.0 \pm 2.9 \pm 1.2$ MeV$/c^2$ and $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV$/c^2$. The estimated branching fraction is $\mathscr{B}(B^+ \to Y(4140)K^+, Y \to J/\psi\phi) = 9.0 \pm 3.4 \pm 2.9 \times 10^{-6}$.

The Belle experiment performs two different searches which are sensitive to a resonance like one observed by CDF. First search is analogous to the CDF search, using $B^+ \to J/\psi\phi K^+$ decays while second is search in $\gamma\gamma \to J/\psi\phi$ reaction. Both searches use almost all available data. In Fig. 4 we show $J/\psi\phi$ invariant mass distribution of both searches. The search in B^+ decays works with 325 ± 21 B^+ signal events on low background. No significant signal is seen. In case of the resonance parameters fixed to the CDF values, we obtain $7.5^{+4.9}_{-4.4}$ signal events and set an upper limit on the branching fraction $\mathscr{B}(B^+ \to Y(4140)K^+, Y \to J/\psi\phi) < 6 \cdot 10^{-6}$ at 90% C.L. The search in $\gamma\gamma$ fusion observes no events around 4140 MeV$/c^2$ and sets an upper limit on $\gamma\gamma$ width times branching fraction $\Gamma_{\gamma\gamma}(Y(4140))\mathscr{B}(Y(4140) \to J/\psi\phi) < 39$ eV/c^2. While there is no direct way of comparing results in B^+ decays and $\gamma\gamma$ fusion, this result indicates that if $Y(4140)$ is real, it is improbable that it would be $D_s^{*+}D_s^{*-}$ molecule.

Additional interesting fact of the mass spectrum of $\gamma\gamma$ fusion search is the cluster of events around 4350 MeV$/c^2$. The fit of the data in the range from 4.2 to 5.0 GeV$/c^2$ yields $8.8^{+4.2}_{-3.2}$ signal events with a 3.9σ statistical significance. If interpreted as resonance, mass is $M = 4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV$/c^2$ and width $\Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1$ MeV$/c^2$.

6. Charged Z states

The last topic to discuss are charged Z states. Charged states have an unique feature that by construction they cannot be accommodated into the conventional $c\bar{c}$ spectrum. Two different final states show positive result up to now. First one was $\psi(2S)\pi^+$ where in the $\overline{B}^0 \to \psi(2S)\pi^+K^-$ decays Belle observed a peak at about 4430 MeV$/c^2$ [20]. Second positive observation is from the $B^0 \to \chi_{c1}\pi^+K^-$ with two resonances in $\chi_{c1}\pi^+$ at masses of about 4050 and 4250 MeV$/c^2$, observed by Belle [21].

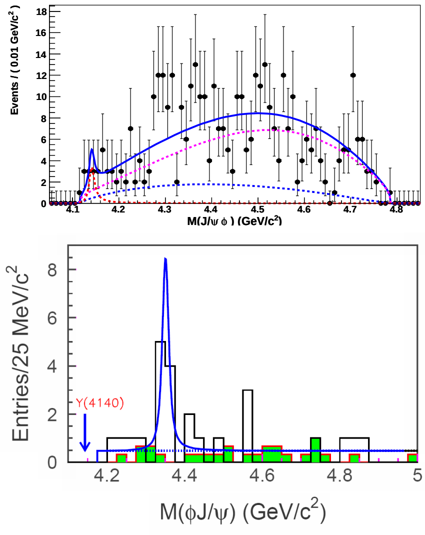

Figure 4: The $J/\psi\phi$ invariant mass distribution obtained by Belle experiment in B decays (top) and $\gamma\gamma$ fusion (bottom). The full line on top represents fit projection, the magenta line B^+ background, the dashed blue line non-B^+ background and the red line signal. In bottom, the open histogram shows data, the filled histogram J/ψ and ϕ sidebands and the blue line fit projection.

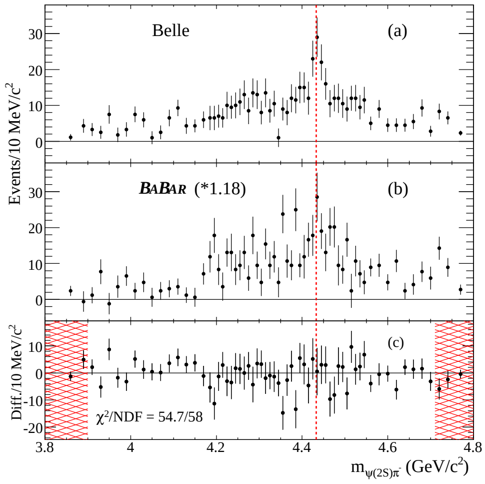

Figure 5: The $\psi(2S)\pi^+$ invariant mass distributions of $\overline{B}^0 \to \psi(2S)\pi^+K^-$ signal from Belle (top), *BABAR* (middle) and difference of the two (bottom). The distribution from *BABAR* is scaled by factor 1.18 to take to account difference in the number of $B\overline{B}$ pairs.

News consist of analysis of $\overline{B}^0 \to \psi(2S)\pi^+K^-$ final state by both B-factories experiments. First, analysis of *BABAR* data was presented [22]. Performing a detailed study of the acceptance and possible reflections they concluded that no significant signal exists in the data. The most significant excess is at mass 4476 ± 8 MeV$/c^2$ with a 2.7σ significance. The mass of this excess is slightly higher than $4433 \pm 4 \pm 1$ MeV$/c^2$ measured at Belle and also shows up mainly in the K^* regions of the Dalitz plot. With the same K^* veto as done in original Belle analysis [20] and resonance parameters fixed to Belle values, small excess with 1.9σ significance is fitted. On the Belle side, original dataset was reanalyzed using original selection and employing a full Dalitz plot ansatz [23]. The new analysis confirms previous result with resonance parameters $M = 4433^{+15}_{-12}{}^{+19}_{-13}$ MeV$/c^2$ and $\Gamma = 107^{+86}_{-43}{}^{+74}_{-56}$ MeV$/c^2$. Main change compare to the original result is an increase in uncertainties, which comes mainly from the uncertainty in Dalitz model. It is worth to note, that while two experiments made different conclusion, the data itself seems to be in a reasonable agreement. In Fig. 5 we show $\psi(2S)\pi^+$ invariant distribution of B^0 signal for both experiments and their difference. As one can see, there is no large discrepancy and it is perhaps only lower available statistics of the *BABAR* experiment, which does not allow to observe the $Z(4430)$.

7. Conclusions

Over the past year both B-factories made progress on studies of XYZ states. The $X(3872)$ received additional attention with several new results and remains the best studied state. Despite the experimental progress, there seems to be no large progress on understanding of the $X(3872)$, except of decreased chance that state seen in $J/\psi\pi^+\pi^-$ is different from the one seen in $D^0\overline{D}^{*0}$. Situation concerning charged Z states basically didn't change, they are still seen only by Belle experiment. *BABAR* performed search for $Z(4430)$, but while data seems to be consistent with Belle, they do not reveal evidence for the state. Other studies performed in the past year revealed some additional information and some signals, but none of them was able to help in the understanding of XYZ states. Altogether there are more states seen than expected and unobserved $c\overline{c}$ states. So if all of them remain, at least some have to be of exotic origin. The progress on experimental side probably needs to wait for future facilities which can perform studies with tenfold statistics.

References

[1] S. K. Choi *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **91** (2003) 262001.

[2] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. Lett.* **93** (2004) 041801.

[3] D. E. Acosta *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **93** (2004) 072001.

[4] V. M. Abazov *et al.* [D0 Collaboration], *Phys. Rev. Lett.* **93** (2004) 162002.

[5] K. Abe *et al.*, arXiv:hep-ex/0505037; B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev.* D **74** (2006) 071101.

[6] A. Abulencia *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **98** (2007) 132002.

[7] G. Gokhroo *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **97** (2006) 162002.

[8] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. D* **77** (2008) 011102.

[9] I. Adachi *et al.* [Belle Collaboration], arXiv:0809.1224 [hep-ex].

[10] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. D* **77** (2008) 111101.

[11] I. Adachi *et al.* [Belle Collaboration], arXiv:0810.0358 [hep-ex].

[12] L. Maiani, A. D. Polosa and V. Riquer, *Phys. Rev. Lett.* **99** (2007) 182003.

[13] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. Lett.* **102** (2009) 132001.

[14] K. Abe *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **94** (2005) 182002.

[15] B. Aubert *et al.* [BaBar Collaboration], *Phys. Rev. Lett.* **101** (2008) 082001.

[16] C. Z. Yuan *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **99** (2007) 182004; B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. Lett.* **95** (2005) 142001; X. L. Wang *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **99** (2007) 142002; B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. Lett.* **98** (2007) 212001.

[17] G. Pakhlova *et al.* [Belle Collaboration], *Phys. Rev. D* **77** (2008) 011103.

[18] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. D* **79** (2009) 092001.

[19] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **102** (2009) 242002.

[20] S. K. Choi *et al.* [BELLE Collaboration], *Phys. Rev. Lett.* **100** (2008) 142001.

[21] R. Mizuk *et al.* [Belle Collaboration], *Phys. Rev. D* **78** (2008) 072004.

[22] B. Aubert *et al.* [*BABAR* Collaboration], *Phys. Rev. D* **79** (2009) 112001.

[23] R. Mizuk *et al.* [BELLE Collaboration], *Phys. Rev. D* **80** (2009) 031104.

PoS(BEAUTY 2009)038