NEW CHARMONIUM-LIKE STATES AT BABAR AND BELLE

R.Mussa
INFN Sezione di Torino, Via Giuria 1
I-10125 Torino, Italy

BaBar and Belle have recently revived the interest in charmonium spectroscopy, discovering many unexpected resonances. In this review, I'll focus mostly on the states found in B decays and double $c\bar{c}$. A better understanding of their production mechanism can help to discriminate among models, confirm tentative J^{PC} assignments, and clarify the overall picture.

1 Introduction

Since the advent of asymmetric B factories, charmonium spectroscopy is living a second renaissance. Beside the discovery of long sought [1] η_c(2S) and h_c(1P), more than half a dozen new states were observed, above the open flavor thresholds. This review will only cover the new charmonium-like resonances observed in B decays, in $\gamma\gamma$, and in $e^+e^- \to c\bar{c}c\bar{c}$. The new vector charmonia found in ISR will be covered by a separate talk [2].

2 Charmonium and charmonium-like objects in B decays

The $B \to (c\bar{c})K$ decays have been extensively studied to investigate the CP violation in weak interactions; as first 'byproduct', came the discovery of the 'true' $\eta_c(2S)$ state. Studies of the multibody processes with a J/ψ, a kaon and other light hadrons led to the discovery of three other resonances, named with the last letters of the alphabet: X(3872), Y(3940), Z(4430). Their nature is still unclear, and their properties are described in the next sections.

2.1 X(3872): molecule, cusp or tetraquark?

In August 2003, Belle [3] reported the discovery of X(3872) in $B \to KX(3872) \to KJ/\psi\pi^+\pi^-$. In rapid sequence, CDF [4], D0 [5] (in $\bar{p}p$ annihilations at $\sqrt{s}$=2 TeV) and BaBar [6] confirmed the discovery. BELLE's upper limit at 90%CL on the total width is $\Gamma < 2.7MeV$. The PDG2006 [7] value for the X(3872) mass (3871.2±0.5) is very close to the $D^0\bar{D}^{*0}$ threshold at 3871.8±0.4 Mev/c^2, updated after the new measurement of the D^0 mass [8]. The quantum numbers of X(3872) are not yet determined: Belle [9] and BaBar [10] observed $X(3872) \to \gamma J/\psi$ (which implies C=+1) with a significance of 4 and 3.4 σ's, respectively. Both CDF [11] and Belle [12] performed an angular analysis of $J/\psi\pi^+\pi^-$: the most likely assignments are $J^{PC} = 1^{++}, 2^{-+}$. Belle [9] claims also the observation of a 4σ signal in $B \to KJ/\psi\pi^+\pi^-\pi^0$ with a rate comparable to the $J/\psi\pi^+\pi^-$ mode. The two- and three- pion mass distributions are clustering on the high end of the spectrum, as if produced from subthreshold $J/\psi\rho$ and $J/\psi\omega$ decays. These evidences suggest that the decay is not conserving isospin, or that X(3872) is not an isospin eigenstate. Last but not least, Belle [13] and BaBar [14] reported evidence of decays to $D\bar{D}\pi$, $\approx 10 \times \mathcal{B}(J/\psi\pi^+\pi^-)$, and $D\bar{D}\gamma$, $\approx 6 \times \mathcal{B}(J/\psi\pi^+\pi^-)$. As the $D\bar{D}\pi$ peak is 3 MeV higher than the $J/\psi\pi^+\pi^-$, theory speculations about a possible doublet of states have started. On the other side, if there is only one state, the sum of observed decays is about to saturate the upper limit set by Babar [16] on $\mathcal{B}$(B $\rightarrow$ K X(3872)), obtained by searching for monochromatic kaon recoils in a tagged B meson sample, where one of the two B mesons is fully reconstructed.

2.2 *Z$^{\pm}$(4430): the first charged resonance with hidden charm content*

Last summer, the Belle collaboration [15] reported about one structure in the $B \rightarrow K\psi'\pi^{\pm}$ Dalitz plot from a sample of 657M $B\bar{B}$ pairs. Outside the known bands corresponding to $K^*(890)$ and $K_2^*(1430)$, a 7 σ bump in the $\psi'\pi^{\pm}$ mass distribution is seen. The state, dubbed Z$^{\pm}$(4430), has a mass M = 4433±4±1 MeV/c^2 and a total width $\Gamma = 44^{+17}_{-13}(stat)^{+30}_{-11}(syst)$ MeV.

Four decay modes of the ψ' are detected: e^+e^-, $\mu^+\mu^-$ and $J/\psi\pi\pi$ with $J/\psi \rightarrow \mu^+\mu^-, e^+e^-$. The resonance is seen both in charged and neutral B decays, but the significance in $B \rightarrow ZK^0_S$ does not exceed 3 σ. If confirmed, this is the first charged tetraquark candidate, and the starting point of a new spectroscopy. Similar structures should be searched for in $\eta_c\pi K$, $J/\psi\pi K$, $\chi_c\pi K$ Dalitz plots. Besides the clear K* signal, statistics are such that a comprehensive study of the complex structure of three-body B decays to charmonium will probably require samples that are not within reach of this generation of B-factories.

2.3 *Y(3940): discovery, confirmation, doubts*

The Y(3940) is a broad resonance, $\Gamma = 92 \pm 24$MeV, discovered by Belle [17] in B decays to $K + \omega J/\psi$. About 1% of the J/ψ's produced in B decays come from this process. If we hypothesize to have just one state, with reasonable assumptions on $\mathcal{B}(Y(3940) \rightarrow J/\psi\omega) \approx 10\%$, its partial width to $J/\psi\omega$ would be $\Gamma(Y(3940) \rightarrow J/\psi\omega) \approx 9MeV$, much larger than the typical widths for hadronic transitions between chatmonia, *e.g.* $\Gamma(\psi' \rightarrow J/\psi\pi\pi) = 0.16$ MeV. Large partial widths of hadronic traditions to low lying states are also observed in the recently found vector states.

The transition with emission of an ω is unique in the charmonium energy range, but has been observed by CLEO [18] in the bottomonium system: $\chi_{b1,2}(2P) \rightarrow \Upsilon(1S)$.

Recently, BaBar [19] has confirmed the observation of a peak in $J/\psi\omega$, but narrower and at a lower energy. The analysis is based on a slightly larger sample, 348 fb^{-1}, and gives M=3914.6±3.6±1.9 MeV/c^2 and Γ = 33±10±5 MeV. While it is simple to isolate the ω peak in the 3π system at higher masses, in the region below 4 GeV also the modeling of the phase space may induce some large systematic error. The $J/\psi\omega$ final state is accessible from almost all possible $c\bar{c}$ quantum numbers, and even an angular analysis would be unreliable, if more states are merging in the same region. The Y(3940) signal still needs to be clarified experimentally, before handing it over to theory speculations.

2.4 *Prospects*

The quantitative picture of the hadronization mechanism which leads from the $b \rightarrow c\bar{c}s$ current at quark level to the final state products is still incomplete. Only 25-45% of the inclusive production of charmonia in B decays [7] (see Table 1) is explained as two body decay to known charmonium and a K or a K*.

Table 1: *Branching ratios (units: 10^{-4}) for B decays to known charmonia (from PDG2006) and to new charmonium-like states. In the rightmost column, feed-down from known transitions is already subtracted from the inclusive rates.*

$\mathcal{B}\times 10^4$	$K^{\pm}$	K^0	$K^{*\pm}$	K^{*0}	+anything
$\mathcal{B}(\eta_c+\mathcal{K})$	9.1 ±1.3	9.1 ±1.9		16 ±7	<90
$\mathcal{B}(J/\psi+\mathcal{K})$	10.08±0.35	8.72±0.33	14.1±0.8	13.3±0.6	78± 3
$\mathcal{B}(\chi_{c0}+\mathcal{K})$	1.6±0.5	<5	<28.6	<7.7	
$\mathcal{B}(\chi_{c1}+\mathcal{K})$	5.3±0.7	3.9±0.4	3.6±0.9	3.2±0.6	31.6±2.5
$\mathcal{B}(\chi_{c2}+\mathcal{K})$	<0.29	<0.26	<0.12	<0.36	16.5±3.1
$\mathcal{B}(\eta_c(2S)+\mathcal{K})$	3.4±1.8				
$\mathcal{B}(\psi'+\mathcal{K})$	6.48±0.45	6.2±0.6	6.7±1.4	7.2±0.8	30.7±2.1
$\mathcal{B}(\psi(3770)+\mathcal{K})$	2.6 ± 0.6 [14]				
$\mathcal{B}(X(3872)+\mathcal{K})\times\mathcal{B}_{J/\psi\pi^+\pi^-}$	$.114\pm.020$				
$\mathcal{B}(X(3872)+\mathcal{K})\times\mathcal{B}_{D^0\bar{D}^0\pi^0}$	1.41 ± 0.40 [13,14]				
$\mathcal{B}(X(3872)+\mathcal{K})$	<2.5 [16]				
$\mathcal{B}(Y(3940)+\mathcal{K})\times\mathcal{B}_{J/\psi\omega}$	$0.15\sim0.71$ [17,19]				
$\mathcal{B}(Z^{\pm}(4430)+\mathcal{K})\times\mathcal{B}_{\psi'\pi}$		$.41\pm.16$ [15]			

3 Two photon physics

Two photon scattering allows to produce C=+1 states of charmonium with $J=even$. Recently, Belle [20] has completed a thorough study of the branching fractions of η_c(1S) and $\chi_{c0,2}$ to 4 charged prongs, and published upper limits for η_c(2S) to the same decay channels.

Above open charm threshold, Belle has probably discovered [21] the $\chi_{c2}(2P)$, decaying to $D\bar{D}$. The measured signal (64±18 events, for a 5.3 σ significance) allows to calculate the product $\Gamma\times\mathcal{B}(\gamma\gamma)\times\mathcal{B}(D\bar{D})=0.18\pm0.05\pm0.03$ keV. A confirmation from BaBar and the measurement of its branching ratio to $D\bar{D}^*$ is needed.

4 Double $c\bar{c}$ in e^+e^- annihilation

Double charmonium production [22] in e^+e^- annihilation, first observed by Belle in 2002, is still a puzzle for theorists. The mass distribution of objects recoiling against J/ψ and ψ' showed clear peaks belonging to η_c,χ_{c0} and $\eta_c(2S)$, discovered in B decays few months before. No signal from the region with $M_{recoil}<M(\eta_c)$ is seen, in disagreement with NRQCD predictions, and the measured $(c\bar{c})(c\bar{c})$ cross section is more than five times bigger than the tree level calculation. Table 2 summarizes the updated experimental results vs NRQCD predictions (LO and NLO).

Table 2: $\sigma(e^+e^-\to V_{c\bar{c}}S_{c\bar{c}})$ *(in fb) vs. NRQCD predictions*

	$V_{c\bar{c}}=J/\psi$,$\mathcal{B}_{S_{c\bar{c}}>2tracks}$				$V_{c\bar{c}}=\psi'$,$\mathcal{B}_{S_{c\bar{c}}>0tracks}$
$S_{c\bar{c}}$	Belle	BaBar	LO	NLO	Belle
$\eta_c(1S)$	25.6±2.8 $\pm$ 3.4	$17.6\pm2.8^{+1.5}_{-2.1}$	3.78±1.26	$17.6^{+7.8}_{-6.3}$	16.3±4.6 $\pm$ 3.9
χ_{c0}	6.4±1.7 $\pm$ 1.0	$10.3\pm2.5^{+1.4}_{-1.8}$	2.40±1.02		12.5±3.8 $\pm$ 3.1
$\eta_c(2S)$	16.5±3.0 $\pm$ 2.4	$16.4\pm3.7^{+2.4}_{-3.0}$	1.57±1.52		16.0±5.1 $\pm$ 3.8

The comparison with theory at full NLO [23] is possible only for the $J/\psi\eta_c$ channel: the resummation of $\mathcal{O}(\alpha_s)$ terms contributes an extra 80%, and $\mathcal{O}(v^2)$ terms give another 145±61%.

The J/ψ recoil method was further refined by Belle, to exploit the dominant decay of states above threshold to D mesons. Reconstructing a large fraction of both charged and neutral D mesons, and exploiting the constraint on M(D), it is possible to single out the D and D* peaks , and resolve the exclusive processes $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$. This allowed to improve the resolution on mass and width of two newly discovered states, named X(3940) [24], and X(4160) [25], and to measure their branching fractions to open charm mesons (see table 3).

Table 3: *Properties of the new states found in double $c\bar{c}$, measured by Belle from a sample of 693 fb* $^{-1}$

State	signif.	M(MeV/c^2)	Γ(MeV)	decay	$\sigma(J/\psi X)\times\mathcal{B}_{out}$(fb)
X(3940)	6.3σ	$3942^{+7}_{-6}\pm 6$	$37^{+26}_{-15}\pm 8$	$D\bar{D}^*$	$13.9^{+6.4}_{-4.1}\pm 2.2$
X(4160)	5.4σ	$4156^{+25}_{-20}\pm 16$	$139^{+111}_{-61}\pm 22$	$D^*\bar{D}^*$	$24.7^{+12.8}_{-8.3}\pm 5.0$

Conventional charmonium interpretations for these states would point to the $\eta_c(3S)$ and $\chi_{c0}(3P)$ states. A confirmation of these states by BaBar is needed, and possibly an angular analysis should be performed to make firmer assessment on the quantum numbers.

Acknowledgments

I'm grateful to my colleagues in Belle and BaBar, who asked me to give this review, and to all the friends in CLEO, CDF and BES who contributed to the heavy quarkonium renaissance. Thanks also to all theorists in the QWG, for many exciting discussions in the recent years.

References

1. N. Brambilla *et al.*, Yellow Report CERN-2005-005, and references therein.
2. E. Grauges, these Proceedings.
3. S. K. Choi *et al.* [Belle Collab.], Phys. Rev. Lett. **91**, 262001 (2003)
4. D. Acosta *et al.* [CDF II Collab.], Phys. Rev. Lett. **93**, 072001 (2004)
5. V. M. Abazov *et al.* [D0 Collab.], Phys. Rev. Lett. **93**, 162002 (2004)
6. B. Aubert *et al.* [BABAR Collab.], Phys. Rev. **D71**, 071103 (2005)
7. W. M. Yao *et al.* [Particle Data Group], J. Phys. **G33**, 1 (2006),
8. C. Cawlfield *et al.* [CLEO Collab.], Phys. Rev. Lett. **98**, 092002 (2007)
9. K. Abe *et al.* [Belle Collab.], arXiv:hep-ex/0505037.
10. B. Aubert *et al.* [BABAR Collab.], Phys. Rev. **D74**, 071101 (2006)
11. M. Kreps [on behalf of CDF], arXiv:hep-ex/0611004(2006); CDF Collab., CDF-PUB-7570.
12. K. Abe *et al.* [Belle Collab.], arXiv:hep-ex/0505038.
13. G. Gokhroo *et al.* [Belle Collab.], Phys. Rev. Lett. **97**, 162002 (2006)
14. B. Aubert *et al.* [BABAR Collab.], Phys. Rev. **D77**, 011102 (2008)
15. S.K. Choi *et al.* [Belle Collab.], Phys. Rev. Lett. **100**, 142001 (2008)
16. B. Aubert *et al.* [BABAR Collab.], Phys. Rev. Lett. **96**, 052002 (2006)
17. S.K. Choi *et al.* [Belle Collab.], Phys. Rev. Lett. **94**, 182002 (2005)
18. H. Severini *et al.* [CLEO Collab.], Phys. Rev. Lett. **92**, 222002 (2004)
19. B. Aubert *et al.* [BaBar Collab.], arXiv:0711.2047 [hep-ex]
20. S. Uehara *et al.* [Belle Collab.], Eur. Phys. J. **C53**, 14 (2008)
21. S. Uehara *et al.* [Belle Collab.], Phys. Rev. Lett. **96**, 082003 (2006)
22. B. D. Yabsley, arXiv:0712.3183 [hep-ex].
23. G. T. Bodwin, J. Lee and C. Yu, arXiv:0710.0995 [hep-ph], ANL-HEP-PR-07-79
24. K. Abe *et al.* [Belle Collab.], Phys. Rev. Lett. **98**, 082001 (2007)
25. K. Adachi *et al.* [Belle Collab.], arXiv:0708.3812 [hep-ex]