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HEAVY QUARKONIA: AN OVERVIEW OF RECENT RESULTS

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Abstract

In the last five years, an impressive amount of new and unexpected results has revived the interest on the study of heavy quarkonia. A comprehensive review on the experimental progress on charmonium and bottomonium spectroscopy, production and decays will be given.

1 Introduction

Since the advent of asymmetric B factories, heavy quarkonium spectroscopy is living a second renaissance. The QWG Yellow Report [1)] on these systems, written only three years ago, to summarize the status of theoretical and experimental understanding of these bound states, can be considered obsolete.

Most of the surprises in spectroscopy are related to states above the open flavor thresholds which decay with unexpectedly large transition rates to the lower narrow states. Production of heavy quarkonia in hadronic interactions is still a challenge for QCD, as recent polarization results from Tevatron [2] are inconsistent with theory predictions. Much progress has been made in NLO calculations to understand the double charmonium production in e^+e^-, but further efforts are needed to sistematically understand the variety of processes which lead to the production of these systems.

2 Charmonium and charmonium-like objects in B decays

The decay of B mesons in charmonium and a kaon has been extensively studied to investigate the CP violation in weak interactions. This has allowed to discover the 'true' $\eta_c(2S)$ state and three (or four?) other resonances, whose nature is still unclear, dubbed with the last letters of the alphabet: X(3872/5), Y(3940), Z(4430).

But the quantitative picture of the hadronization mechanism which leads from the $b \to c\bar{c}s$ current at quark level to the final state products is still incomplete. Table 1 shows the PDG2006 [3] values for the branching ratios of B decays to charmonium known states and the two lowest strange mesons, or anything. By filling the missing slots we may get more clues to the nature of the new states.

Table 1: *B decays to charmonium known states*

$\mathcal{B} \times 10^4$	K$^\pm$	K^0	K$^{*\pm}$	K^{*0}	+anything
η_c	9.1 $\pm$1.3	9.1 $\pm$1.9		16 $\pm$7	< 90
J/ψ	10.08$\pm$0.35	8.72$\pm$0.33	14.1$\pm$0.8	13.3$\pm$0.6	78$\pm$ 3
χ_{c0}	1.6$\pm$0.5	< 5	< 28.6	< 7.7	
χ_{c1}	5.3$\pm$0.7	3.9$\pm$0.4	3.6$\pm$0.9	3.2$\pm$0.6	31.6$\pm$2.5
χ_{c2}	< 0.29	< 0.26	< 0.12	< 0.36	16.5$\pm$3.1
$\eta_c(2S)$	3.4$\pm$1.8				
ψ'	6.48$\pm$0.45	6.2$\pm$0.6	6.7$\pm$1.4	7.2$\pm$0.8	30.7$\pm$2.1

The table shows that only 25-45% of the inclusive rate to charmonia is explained as a two body decay to charmonium and a pseudoscalar or vector kaon. Feed-down from known transitions (e.g.$\psi' \to \chi_c\gamma$) is already subtracted from the inclusive rates, in the last column. Which other process is responsible for the remaining $J/\psi, \psi'$'s produced in B decays? Multi-body, higher kaon excitations, or higher charmonia?

2.1 X(3872) and X(3875) : the first tetraquark doublet?

In August 2003, BELLE [4] reported the discovery of X(3872) in:

$$B \to KX(3872) \to J/\psi\pi^+\pi^-$$

One month after, CDF [5] confirmed the existence of the such state, observing it in the same decay channel, but producing it more copiously in prompt $\bar{p}p$ annihilation at $\sqrt{s}$=2 TeV: only 16% of their X(3872) candidate events come from B decays. In the following years, D0 [6] and BABAR [7] confirmed these observations.

The width of X(3872) has not been measured yet: BELLE set the upper limit $\Gamma < 2.7MeV$ at 95% C.L.). The PDG 2007 value for the X(3872) mass (3871.4±0.6) is close to a cluster of thresholds, summarized in table 2; in particular it is just below $M(D^0)$+$M(\bar{D}^{*0})$. CLEO [8] has recently re-measured the D^0 mass, to reduce the statistical and systematical error on the $D^0\bar{D}^{*0}$ threshold.

Table 2: *Thresholds in the proximity of X(3872)*

Final state	$J/\psi\rho$	$J/\psi\omega$	$D^0\bar{D}^{*0}$	$D^{\pm}D^{*\mp}$
Threshold	3872.4±0.3	3879.57±0.12	3871.8±0.4	3879.9±0.4

The evidence (BELLE [9], BABAR [10]) of X(3872) decays to $\gamma J/\psi$ imposes C=+1 for the state. Such results were obtained with samples of 275M (287M) B decays from BELLE (BABAR) and had a significance of 4(3.4) σ's. At present, both experiments have doubled their statistics and should exploit them to reinforce such assessment.

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. Even if the ω threshold is 7 MeV above, the three pions are clustering at the high end of their mass spectrum and seem to originate from the decay of a $J/\psi - \omega$ bound state. These evidences indicate that the decay is not conserving isospin, or that the state is not an isospin eigenstate.

Both CDF [11] and BELLE [12] performed an angular analysis on the $J/\psi\pi^+\pi^-$ reaction: the most likely assignments are $J^{PC} = 1^{++}, 2^{-+}$. The

J=2 assignment, though unfavored, cannot be ruled out, as the B coupling is anyway very small: BABAR and BELLE measure:

$$\mathcal{B}(B^+ \to K^+ X(3872)) * \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.14 \pm 0.20) \times 10^{-5}$$

Can we obtain an absolute value for $\mathcal{B}(B^+ \to K^+ X(3872))$? In principle, it can be obtained from a sample of fully reconstructed B mesons at the Y(4S) peak; by searching for a K in the decay products of the other B meson, and looking for peaks in the inclusive spectrum of what recoils against this kaon, BABAR [13] could set upper limits on $\mathcal{B}$(B $\to$ K X)< 2.5 * 10^{-4}.

A large variety of hypotheses have been made in the last years [14] on the nature of X(3872): $D\bar{D}^*$ molecule, cusp, tetraquark. The most appealing implication of the tetraquark model [15] is a set of predictions on possible charged partners which can be verified experimentally, but so far no candidates have been found in the proximity of X(3872). The tetraquark model predicts the hypothesis of the existence of a doublet of neutral states, and BELLE [16] and BABAR [17] reported the evidence of a peak in $D\bar{D}\pi$ approximately 3 MeV above the PDG average for the $J/\psi\pi\pi$ evidence. BELLE measures:

$$\mathcal{B}(B \to KX \to KJ/\psi\pi\pi)/\mathcal{B}(B \to KX \to D\bar{D}\pi) \approx 10\%$$

BABAR also reports an excess in the $D\bar{D}\gamma$ channel, with a branching ratio which is consistent with $\mathcal{B}(D^{0*} \to \gamma D^0)/\mathcal{B}(D^{0*} \to \pi^0 D^0) = 62\%$

Observation of a $D\bar{D}^*$ signal is quite challenging for CDF, but can provide further interesting informations on this state, as the cross check is based on a different production mechanism. Even without detecting the photon or the π^0, feeddown from X(3872) should produce a bump below $\psi(3770)$ in the $D\bar{D}$ mass plot.

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

This summer, the BELLE collaboration [18] showed one more structure in the $B \to K\psi'\pi^\pm$ 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 $J/\psi \to \mu^+\mu^-, e^+e^-$. The resonance, is seen both in charged and neutral B decays, but the significance in $B \to Z K^0_S$ does not exceed 3 σ. The measured product of branching fractions is

$$\mathcal{B}(B \to K Z^+(4430)) \times \mathcal{B}(Z^+(4430) \to \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$$

. This evidence opens a Pandora box: can we expect similar structures in the Dalitz plots of B decays to K, π and a lower lying charmonium resonance? How can we exclude possible artefacts from the interference between many broad kaon resonances between 1.2 and 1.9 GeV? BELLE analysis has excluded possible effects from the interference of up to three partial waves, but, with lower lying charmonia, the number of $K\pi$ excitations is going to be larger.

Significantly higher statistics is probably needed to resolve the complex structure of the three-body B decays to charmonium.

2.3 Y(3940): discovery, confirmation, doubts

The Y(3940) is a very broad resonance ($\Gamma = 92 \pm 24$MeV) discovered by BELLE [19] in B decays to $K\omega J/\psi$. The product of branching ratios is

$$\mathcal{B}(B \to Y(3940)K) * \mathcal{B}(Y(3940) \to J/\psi\omega) = (7.1 \pm 1.5 \pm 3.1) * 10^{-5}$$

If we assume to have just one state, and guess that $\mathcal{B}(B \to KY(3940)) < 4 * 10^{-4}$, we anyway get $\mathcal{B}(Y(3940) \to J/\psi\omega)) > 12\%$, and its partial width to $J/\psi\omega$ would be $\Gamma(Y(3940) \to J/\psi\omega) > 7MeV$, by far the largest width for an hadronic transition between charmonia - to be compared with, for instance, $\Gamma(\psi' \to J/\psi\pi\pi) = 0.16$ MeV.

The transition with emission of an ω is unique in the charmonium energy range, but has been observed by CLEO [20] in the bottomonium system: $\chi_{b1,2}(2P) \to \Upsilon(1S)$. Another possible insight on its nature is the proximity of the $D_s\bar{D}_s$ threshold, at 3936 MeV.

Recently, BABAR [21] 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 $\Gamma = 33 \pm 10 \pm 5$ MeV. While it is simple to isolate the ω peak in the 3π system at higher energy, 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 give a confusing output, if more states are merging in the same bump. The

Y(3940) signal still needs to be clarified experimentally, before handing it over to theory speculations.

3 Two photon physics

Two photon scattering allows to produce C=+1 states of charmonium with $J = even$. A review of the comprehensive study on the $\gamma\gamma$ production of lower charmonia is given from S.Eidelman [31] at this conference. Above open charm threshold, BELLE has discovered [22] 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 $\Gamma \times \mathcal{B}(\gamma\gamma) \times \mathcal{B}(D\bar{D}) = 0.18 \pm 0.05 \pm 0.03$ keV. A confirmation from BABAR and the measurement of its branching ratio to $D\bar{D}^*$ and $D^*\bar{D}^*$ is needed.

4 Modern scanning with radiative return

The high luminosity available to asymmetric B factories allows them to turn the initial state radiation in a powerful tool for scanning the energy region across the open charm threshold, as well as the narrow Y(nS) resonances, with unprecedented statistical power.

4.1 New vector states: the Y(4260,4350,4660)

The ISR scanning is rapidly changing our whole understanding of vector charmonia. Only two years ago, BABAR [23] discovered the Y(4260), in the process $e^+e^- \to J/\psi\pi\pi$. Such discovery was soon confirmed by CLEO [24] and BELLE [25], who found the peak in their ISR data. The most recent values of the Y(4260) mass from these three experiments are summarized in the table 3.

Table 3: *Y(4260): mass and width measurements*

Experiment	M(MeV/c^2)	Γ(MeV)
BABAR	$4258 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
BELLE	4263 ± 6	126 ± 18
CLEO	$4283^{+17}_{-16} \pm 4$	$70^{+10}_{-25} \pm 5$

CLEO-c [26] has then taken one data point (12 pb^{-1}) at $\sqrt{s} = 4.26$ finding an excess in $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, and $J/\psi K\bar{K}$. As the real peak position is uncertain, only relative rates can be extracted from these data.

Hybrid charmonium ($c\bar{c}g$) or tetraquark ($cs\bar{s}\bar{c}$) are the most popular theoretical interpretations for this state at the moment.

Searching for the transition $Y(4260) \to \psi'\pi\pi$, BABAR finds evidence [27] of another state, named Y(4350), 90 MeV above the Y(4260) peak. This discovery is confirmed by BELLE soon after: the higher statistics allows to resolve a second peak, dubbed Y(4660) [28]. Both Y(4350) and Y(4660) do not seem to decay to $J/\psi\pi\pi$, a fact that still lacks theoretical explanation. All these states have a large branching ratio to the lower lying charmonia, while the coupling to open charm mesons is suppressed. The unexpected discovery of a new window to access lower charmonia may open new roads to search for the still missing narrow D states.

At this conference, BELLE has shown [29] the first hint of a possible bottomonium counterpart of the Y(4260): the Y(5S) transition rate to Y(1,2S) states is much large than the one of Y(4S). Only a scan [30] around the Y(5S) will allow to confirm the discovery of the first Y_b candidate.

4.2 Complete exclusive decomposition of the R scan from 3.8 to 5 GeV

The study of exclusive channels in ISR not only led to the discovery of new vector states but also allowed to understand better the wide resonances which decay to open charm and were measured from the R scans done by DASP, Mark I, Crystal Ball and BES. Such bumps, known as $\psi(4040), \psi(4160), \psi(4415)$ are listed in the PDG since decades, but without any details on the branching fractions to exclusive channels with charmed mesons.

Recently, CLEO scanned the 3.9-4.2 GeV region to optimize the yields of D and Ds mesons with a twelve point scan, and exclusive results on six two body channels ($D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s{}^{(*)}$) were published last year. The physics reach of such scan goes beyond the above mentioned purpose, as it casts light on the evolution of the R ratio across the resonance region.

Exploiting the large amount of ISR luminosity (22 pb^{-1}/0.1 GeV in the $\sqrt{s} \approx 4GeV$ region) and the excellent performance of its particle ID, BELLE has completed [31] the decomposition of the hadronic cross section into exclusive reactions $D\bar{D}$, $D^*\bar{D}$+c.c., $D^*\bar{D}^*$, and even $D\bar{D}_2^*(2460)$. The most unexpected result from this analysis is the $D\bar{D}_2^*(2460)$ dominance in the $\psi(4415)$ signal [32], which may indicate a large D wave contribution to this charmonium state.

The sum of the exclusive channels saturates the $e^+e^- \to hadrons$ signal in this range, with the present statistical errors. Contributions from those channels with non strange mesons will allow to compute branching fractions and compare them with the theory predictions, mainly based on the Cornell coupled channel model.

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

Double charmonium production [33] in e^+e^- annihilation, first observed by BELLE in 2002, has been challenging theory predictions based on NRQCD since its discovery. The CM momentum spectrum of inclusive J/ψ's showed an abrupt loss of events much before the kinematical limit, where the color octet term is expected to give a dominant contribution. The mass distribution of objects recoiling against J/ψ and ψ' showed clear peaks belonging to η_c, χ_{c0} and η_c', discovered in B decays few months before. BELLE's signal has been later confirmed by BABAR.

Essentially, the signal from the region with $M_{recoil} < M(\eta_c)$ is consistent with zero, in disagreement with NRQCD predictions. On the other hand, the measured double charmonium cross section is more than five times bigger than the tree level NRQCD prediction. Higher order corrections in α_S and in the quark velocity are quite large.

Table 4 summarizes the updated experimental results vs NRQCD predictions (LO and NLO).

Table 4: $\sigma(e^+e^- \to V_{c\bar{c}}S_{c\bar{c}})$ *(in fb) vs. NRQCD predictions*

$V_{c\bar{c}}; S_{c\bar{c}}$	BELLE	BABAR	LO	NLO
$J/\psi; \eta_c(1S), \mathcal{B}_{>2}$	$25.6 \pm 2.8 \pm 3.4$	$17.6 \pm 2.8^{+1.5}_{-2.1}$	3.78 ± 1.26	$17.6^{+7.8}_{-6.3}$
$J/\psi; \chi_{c0}, \mathcal{B}_{>2}$	$6.4 \pm 1.7 \pm 1.0$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	2.40 ± 1.02	
$J/\psi; \eta_c(2S), \mathcal{B}_{>2}$	$16.5 \pm 3.0 \pm 2.4$	$16.4 \pm 3.7^{+2.4}_{-3.0}$	1.57 ± 1.52	
$\psi'; \eta_c(1S)\mathcal{B}_{>0}$	$16.3 \pm 4.6 \pm 3.9$	-		
$\psi'; \chi_{c0}, \mathcal{B}_{>0}$	$12.5 \pm 3.8 \pm 3.1$	-		
$\psi'; \eta_c(2S), \mathcal{B}_{>0}$	$16.0 \pm 5.1 \pm 3.8$	-		

The comparison with theory calculations at full NLO [34] is possible only for the $J/\psi\eta_c$ channel and shows that an extra 80% is coming from resummation of O(α_s) terms, but an even larger contribution, 145±61% is expected from the higher order terms in v^2. From an experimentalist point of view, below open charm threshold, the challenge is represented by the detection of the $\chi_{c1,2}$ states between the χ_{c0} and $\eta_c(2S)$ peaks, which would allow to quantify the suppression of higher angular momenta in this process.

Given the dominance of NLO terms, theory calculations should be extended to higher orders to test their stability, in order to give a robust pattern of testable predictions on all lower lying C=+1 charmonia (i.e. not just J=0 ones). A good understanding of the double charmonium process below the open charm threshold is necessary, if we want to make statements on the quantum numbers of the other two bumps discovered above 3.8 GeV in the same process, which are described below.

5.1 Spectroscopy advances via the J/ψ recoil method

The J/ψ recoil method led BELLE to the discovery of two new resonances, dubbed X(3940) [35], and the X(4160) [36]. Both states have a significant decay rate to D* mesons, and the recoil technique has been further refined. By fully 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 these states, and to measure their branching fractions to open charm mesons: results from a sample of 693 fb^{-1} are summarized in table 5. Also the $e^+e^- \to J/\psi D\bar{D}$ cross section shows structures, that need more statistics to be resolved.

Table 5: *Properties of the new states found in double $c\bar{c}$*

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, as well as further studies to detect them in other processes, e.g. from $\gamma\gamma$ or B decays.

6 The search for parabottomonia

The known bottomonium spectrum is far from complete: all the spin singlet states, i.e. the $\eta_b(1, 2, 3S)$ and the $h_b(1, 2P)$ have not been found yet. Ironically enough, NRQCD is expected to yield reliable predictions especially for the lower lying parabottomonia, e.g. the $\eta_b(1S)$ mass is expected to be 9421 MeV at NLO [37], with a theory error (10 MeV) which is comparable to the one (9 MeV) due to the uncertainty on $\alpha_s(M_Z)$, and the NNLL estimate [38] of its two photon width at NNLL (0.66±0.09 keV), shows a remarkable stability with the renormalization scale.

CLEO-III data samples taken between 2001 and 2002 on the Y(nS) narrow resonances have been thoroughly analized [39], to search inclusively for the signatures of the radiative transitions $Y(2, 3S) \to \gamma\eta_b(1, 2S)$ and the double transitions $Y(3S) \to h_b(\pi^0, \pi^+\pi^-); h_b \to \eta_b\gamma$, resulting in upper limits which can rule out several theory predictions. Further studies on these samples are still under way, and will hopefully lead to the discovery of the η_b.

The asymmetric B factories have a large unexploited potential on these searches, as their ISR samples are comparable to the data taken by CLEO-III, but the indetermination on the energy of the radiative return prevents from doing inclusive searches. Recently, the BELLE collaboration has taken a record sample of 11M Y(3S) decays in less than a week of running time at the Y(3S) energy, which are currently being analyzed to improve CLEO limits, and hopefully to discover the long awaited parabottomonia. Anyway, an extensive program for the study of the whole parabottomonium spectrum will probably require at least ten times larger samples.

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