YXYZX ROADS: CHARMONIUM AND BEYOND

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The discovery of X(3872) has opened a new golden age for studies on heavy quarkonia. Since August 2003, five new states were observed in the energy region around the open charm thresholds: X(3872), Z(3930), Y(3940), X(3943) and Y(4260) are currently challenging the theoretical understanding on charmonium spectrum, and in some cases may hint towards new types of hadronic matter: hybrids, tetraquarks, hadromolecules.

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1. The XYZ revolution

The interest in charmonium spectroscopy has been revitalized, in the recent years, by the re-discovery of long sought missing narrow states ($\eta_c(2S)$ and h_c), and the observation of new unexpected resonances. An extensive review on heavy quarkonium physics can be found in Ref.1. A major impulse to this wave of discoveries comes from the asymmetric beauty factories. The record luminosities achieved by these machines are certainly one of the key factors for the discovery potential of Belle and BaBar. New charmonium states are accessible in a wide variety of production modes: B decays, photon-photon fusion, radiative return, double charmonium. These experiments are perfectly complemented by CDF and D0 at Tevatron and by Cleo at Cornell, and will soon be joined by the upgraded BES-III at Beijing. This mini-review focuses on the new charmonium-like states, dubbed X's, Y's and Z, which have been found in the last three years, in the energy region where decay modes with charmed mesons open up and various threshold effect can distort the orthodox charmonium spectrum.

2. X(3872)

Belle[2] discovered X(3872) in:

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

The discovery was announced in August 2003: after one month, CDF [3] 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: only 16% of their X(3872) candidate events come from B decays.

The observation (Belle[4], BaBar[5]) of X(3872) decays to $\gamma J/\psi$ imposes C=+1 for the state. In the same paper, Belle claims the observation of a 4σ signal in

$$B \to KJ/\psi\pi^+\pi^-\pi^0$$

with a rate comparable with the $J/\psi\pi\pi$ mode. These evidences indicate that the decay is not conserving isospin, or that the state is not an isospin eigenstate.

Both CDF[6] and Belle[7] have performed an angular analysis on the $J/\psi\pi\pi$ reaction, rejecting a large number of J^{PC} assignations. Only 1^{++} and 2^{-+} survive , in CDF paper, while Belle favors 1^{++}, over 0^{++} and 0^{-+} (these three assignments are favored by factorization in B decays to $K + c\bar{c}$).

A detailed theoretical review on X(3872) can be found in Ref.8. Even if 1^{++} assignment seems very likely, it does not necessarily mean that we are observing the radial excitation of χ_{c1}, that is expected by many models to lie about 40 MeV higher in energy. Given the proximity of the $D^0\bar{D}^{0*}$ threshold, X(3872) can also be interpreted as a $D\bar{D}^*$

molecule[9], or a threshold cusp[10]. The improved measurement of the D^0 meson mass, by Cleo,[11] shifts 0.5 MeV up the $D\bar{D}^*$ threshold, giving further support to the molecular hypothesis: $M(X) - M(D_0) - M(D_0^*) = -0.4 \pm 0.7$MeV.

Interpretation of the X as a four quark state [12] has a number of implications that can be verified experimentally. One is the existence of charged partners: BaBar set upper limits (90% CL) at 5.4*10^{-6} on BR($B^0 \to K^+X^- \to K^+\pi^-\pi^o J/\psi$) and at 22*$10^{-6}$ on BR($B^- \to K^0X^- \to K^+\pi^-\pi^o J/\psi$). Another interesting implication is a splitting between the $X_u = \bar{c}\bar{u}uc$ (which is produced in $B^+ \to K^+X_u$) and the $\bar{c}\bar{d}dc$ state (which is produced in $B^0 \to K^0X_d$). BaBar [13] measured M(X_u)-M(X_d) $= 2.7 \pm 1.3 \pm 0.2$ MeV/c^2, and the ratio $BR(B^0 \to K^0X_d)/BR(B^+ \to K^+X_u) = 0.61 \pm 0.36 \pm 0.06$

Recently, Belle [14] reported the evidence of a peak in $D\bar{D}\pi$ at $\sqrt{s} = 3875.4 \pm 0.7^{+0.7}_{-1.7} \pm 0.8$ MeV/c^2. The discrepancy in invariant mass is puzzling , and may suggest the existence of a doublet of states. It is crucial to have an independent check by BaBar. Given the high rate of X(3872) production in hadronic collision, the study of the $D\bar{D}^*$ invariant mass at CDF is likely to provide other important informations. Belle measures $BR(X(3872) \to J/\psi\pi\pi)/BR(X \to D\bar{D}\pi \approx 10\%$; a discrepancy on this number in hadronic production will support the doublet hypothesis.

Belle and BaBar measure the product BR($B^+ \to K^+X(3872)$)*BR($X(3872) \to J/\psi\pi\pi$), and the average gives 1.15*10^{-5}. Can we obtain an absolute value for the BR($X(3872) \to J/\psi\pi\pi$) alone? An analysis pioneered by Babar tags the recoil K from B decays and studies the invariant mass of the state recoiling on the kaon. This allows to measure BR(B $\to$ K X) inclusively; combining the two results, the lower limit BR($X \to J/\psi\pi\pi$) >4.2% (at 90%CL) is obtained.

3. Z(3930)

The Z(3930) is the newly discovered state which fits more easily within the charmonium spectrum. It was observed by Belle [15] in $\gamma\gamma \to D\bar{D}$ with a mass M = 3929±5±2 MeV/c^2 and width Γ = 29±10±2 MeV.

The study of its angular distribution favors 2^{++}, suggesting that it may be the $\chi_{c2}(2P)$, even if most theory predictions place it about 50 MeV higher . Such interpretation conflicts with the $\chi_{c1}(2P)$ hypothesis for X(3872), as the fine splitting between these two states would be 57 MeV (to be compared with the 45 MeV of the ground P states) and therefore gives further support to the molecular explanation for the X(3872).

It is now important to search for the $D\bar{D}^*$ decay mode, to measure the ratio $D\bar{D}^* : D\bar{D}$ (theory predicts $\approx$ 1:3), and to search for the radiative decays to J/ψ or ψ'. On the other hand, production rates in gluon-gluon fusion should be measurable at CDF by searching for the decay in $D\bar{D}$ or $D\bar{D}^*$.

4. X(3943)

The X(3943) corresponds to a bump seen by Belle[16] in $e^+e^- \to J/\psi + X$, in the invariant mass spectrum of states recoiling against J/ψ. Further analysis of the final products shows positive (BR($D\bar{D}^*$) >45% at 90% CL) evidence of $D\bar{D}^*$ decay and negative (BR($D\bar{D}$) <41% at 90% CL) of $D\bar{D}$. The significance of the signal is 5σ. A search for the exclusive signal $e^+e^- \to J/\psi X(3943) \to J/\psi J/\psi\omega$ gave the upper limit $BR(X(3943) \to J/\psi\omega) < 21\%$ at 90% CL. The limits are not very stringent yet, and more statistics is needed.

The quasi-exclusive peak (M=3943±6 MeV/c^2, Γ=15±10 MeV) looks narrower than - but statistically consistent with -

the inclusive one (M=3936±14 MeV/c^2, Γ=39±26 MeV), suggesting that more than one state can merge in this interesting region. As the three other peaks observed in the recoil spectrum correspond to the known $\eta_c(1S), \chi_{c0}(1P), \eta_c(2S)$ charmonium states, the natural candidate is the next pseudoscalar excitation, i.e. the $\eta_c(3S)$. Theory predicts a width of 50 MeV for this state, and a smaller hyperfine splitting with its vector partner, the $\psi(4040)$. Threshold effects may explain this discrepancy.

Further studies are needed to confirm these quantum numbers: study the angular distribution, and search for other decay modes, such as $K\bar{K}\pi$. Hopefully, BaBar will soon contribute to better understand this state, adding statistics and possibly some evidence in other decay or production modes.

5. Y(3940)

Searches for a signal from the X(3943) and the Z(3930) in B decays to $KD\bar{D}$ or $KD\bar{D}^*$ have given no results so far . In the same energy region, Belle[17] observes a much broader peak ($\Gamma = 92 \pm 24$MeV) in B decays to $J/\psi\omega \rightarrow J/\psi\pi\pi\pi$. Such state, dubbed Y(3940), still lacks both a clear experimental signature and a theory explanation.

The product of branching ratios is $BR(B \rightarrow Y(3940)K) * BR(Y(3940) \rightarrow J/\psi\omega) = (7.1 \pm 1.5 \pm 3.1) * 10^{-5}$. If we assume to have just one state, and guess that $BR(B \rightarrow KY(3940)) < 4 * 10^{-4}$, we anyway get $BR(Y(3940) \rightarrow J/\psi\omega)) > 12\%$, and its partial width to $J/\psi\omega$ would be $\Gamma(Y(3940) \rightarrow J/\psi\omega) > 7MeV$, by far the largest width for an hadronic transition between charmonia - to be compared with, for instance, $\Gamma(\psi' \rightarrow J/\psi\pi\pi) = 0.16$ MeV.

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

The Y(3940) signal still needs to be clarified experimentally, before handing it over to theory speculations. It may be somehow related to the X(3943) and the Z(3930) states, merged with some still unknown resonance with different quantum numbers. In such case, any angular analysis would be useless. Even in this case, an independent confirmation from BaBar or Cleo is still missing; Belle should do a detailed study of the phase space for this 4-body final state, to have a firmer assessment on the significance of the signal.

6. Y(4260) ... and Y(4350)

Even in the list of vector charmonia there is a new entry. BaBar exploited the radiative return to scan the process $e^+e^- \rightarrow J/\psi\pi\pi$ in a very wide energy range, and observed[19] a peak at $\sqrt{s}$=4.26 GeV, exactly where the the cross section $e^+e^- \rightarrow hadrons$ has a dip. The partial width for this transition is $\Gamma(Y(4260) \rightarrow J/\psi\pi\pi) > 7.7 \pm 2.1$ MeV, which is again a very large number for a quarkonium transition. Babar also reported[20] about a 3.1σ evidence of Y(4260) in B decays to $KJ/\psi\pi\pi$.

The discovery was confirmed by Cleo[21] and Belle,[14] who found the peak in their ISR data. The three mass measurements are slightly incompatible, as summarized in the table 1.

Table 1. Y(4260): mass and width measurements

Exp.	M(MeV/c^2)	Γ(MeV)
BaBar	$4258 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
Belle	$4295 \pm 10^{+11}_{-5}$	$133 \pm 23^{+6}_{-4}$
Cleo	$4283^{+17}_{-16} \pm 4$	$70^{+10}_{-25} \pm 5$

Cleo-c[22] 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.

The state lies between two open charm

thresholds: $D_s^* \bar{D}_s^*$ at 4224 MeV and $D_1(2420)\bar{D}$ at 4290 MeV; a precise measurement of its mass is quite important to understand its nature. Using the data taken at 4.26, Cleo's results [21] already allow to exclude interpretations of Y(4260) as oddball, $\chi_c \rho$ molecule or baryonium.

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. If Y(4260) is an hybrid , its dominant decay should be $D_1(2420)\bar{D}$, and the deconvolution of the exclusive channel $e^+e^- \to D\pi\bar{D}^*$ from other two- body or three body channels including $D^{(*)}$ mesons is quite challenging: preliminary results from both Cleo[21] and Belle[14] have been shown at this conference.

Interpretation of this state as $\psi(4S)$ would make the pattern of charmonium vector states remarkably similar to its bottomonium counterpart, but is inconsistent with all recent calculations of charmonium spectra.

Searching for the transition $Y(4260) \to \psi'\pi\pi$, BaBar finds evidence [5] of a signal, but 90 MeV above the Y(4260) peak: will we call it Y(4350)? These results show that even the 1^{--} sector is not fully under control, and provide fertile seeds for the forecoming BES-III experiment, as well as for the running experiments, which will likely double their statistics in the next two years.

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