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

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On behalf of the Belle and BABAR Collaborations
Below open charm threshold all states observed with good agreement between theory and experiment.

Above threshold many states predicted and observed, but without good match.

Several states above threshold considered as candidates for exotic hadrons.

Impossible to cover all results.

Try to select most interesting/important ones.
$X(3872) \rightarrow J/\psi \pi \pi$

Phys. Rev. D77, 111101, (2008)

$93.4 \pm 17.2$

8.5σ

$B^+ \rightarrow \chi K^+$

$657M \ B \bar{B} \text{ pairs}$

$9.4 \pm 5.2$

2.3σ

$B^0 \rightarrow \chi K_S$

$455M \ B \bar{B} \text{ pairs}$

$131.7 \pm 15$

12.8σ

$27.6 \pm 6.6$

5.9σ
### X(3872) → J/ψππ

#### Table

|                  | Belle                        | Babar                        |
|------------------|------------------------------|------------------------------|
| $M_X$ [MeV]      | 3871.46 ± 0.37 ± 0.07        | 3871.4 ± 0.6 ± 0.1           |
| $\delta M$ [MeV] | 0.18 ± 0.89 ± 0.26           | 2.7 ± 1.6 ± 0.4              |
| $R \left( \frac{B^0 \to X K^0}{B^+ \to X K^+} \right)$ | 0.82 ± 0.22 ± 0.05           | 0.41 ± 0.24 ± 0.05           |

#### Molecule:
- Expect mass below $D^0 D^{*0}$
- Consistent, but mass above not excluded

#### Tetraquark:
- Maiani et al. predict $\delta M = 8 \pm 3$ MeV
- Does not exclude tetraquark, only disfavors particular model
B$^0 \rightarrow X(3872)K\pi$

Belle performed study of $B^0 \rightarrow X(3872)K\pi$ with $X(3872) \rightarrow J/\psi\pi\pi$

$N_{XK\pi} = 81 \pm 20, \ N_{XK^*} = 8 \pm 10$

$\mathcal{B}(B \rightarrow X(K\pi)_{non-res}) \cdot (X \rightarrow J/\psi\pi\pi) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$

$\mathcal{B}(B \rightarrow XK^*) \cdot (X \rightarrow J/\psi\pi\pi) < 3.4 \times 10^{-6} @ 90\% \ C.L.$

Non-resonant component is dominant, $K^*$ component small

In contrast to $B$ decays to $\psi(2S)$, $J/\psi$ or $\chi_{c1}$
$X(3872) \rightarrow \psi(2S)\gamma$

- $X(3872)$ decays to $c\bar{c}$-mesons and $\gamma$ can distinguish molecule from conventional $c\bar{c}$
- Evidence for decays to both final states
  \[ N(J/\psi\gamma) = 23.0 \pm 6.4 \pm 0.6 \ (3.6\sigma) \]
  \[ N(\psi(2S)\gamma) = 25.4 \pm 7.3 \pm 0.7 \ (3.5\sigma) \]
- $\frac{B(X \rightarrow \psi(2S)\gamma)}{B(X \rightarrow J/\psi\gamma)} = 3.4 \pm 1.4$
- Fixes $C$ to be positive
- Generally inconsistent with pure $D^0\bar{D}^{*0}$ molecule
- If molecule, then mixing with a significant $c\bar{c}$ component
$X(3872) \rightarrow \overline{D}D^*$

657M $B\overline{B}$ pairs

$D^*0 \rightarrow D^0 \gamma$

$D^*0 \rightarrow D^0 \pi^0$

$M_{bc}>5.27$ GeV

$M(BW) = 3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV

$M(BW) = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV

New Belle measurement show no significant difference to $M$ in $J/\psi\pi\pi$ channel.

→ Need to be careful with BW close to threshold
→ We may be seeing only the tail
**States around 3940 MeV**

| state      | mass [MeV]      | width [MeV]    |
|------------|-----------------|----------------|
| $Y(3940)$  | $3943 \pm 11 \pm 13$ | $87 \pm 22 \pm 26$ |
| $Y(3940)$  | $3914.3^{+3.8}_{-3.4} \pm 1.6$ | $33^{+12}_{-8} \pm 0.6$ |
| $X(3915)$  | $3914 \pm 3 \pm 2$      | $23 \pm 10^{+2}_{-8}$      |
| $\chi'_{c2}$ | $3929 \pm 5 \pm 2$      | $29 \pm 10 \pm 2$      |

Is $X(3915)$ new state, $\chi'_{c2}$ or $Y(3940)$?

$$\gamma\gamma \rightarrow X(3915) \rightarrow J/\psi \omega$$

$N_s = 55 \pm 14^{+2}_{-14}, 7.7\sigma$

**Phys. Rev. Lett. 94, 182002, (2005)**

$B^+ \rightarrow YK^+, Y \rightarrow J/\psi \omega$

**Phys. Rev. Lett. 101, 082001, (2008)**
Y Family @ ISR

\( e^+ e^- \rightarrow J/\psi \pi \pi \gamma_{ISR} \)

Phys. Rev. Lett. 99, 182004, (2007)

- Solution I
- Solution II

\( e^+ e^- \rightarrow \psi(2S) \pi \pi \gamma_{ISR} \)

Phys. Rev. Lett. 99, 142002, (2007)

Y(4080)  Y(4260)  Y(4360)  Y(4660)  Y(4660)?

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Y Family @ ISR

Phys. Rev. D79, 092001, (2009)

Phys. Rev. D77, 011103, (2008)
## Y Family @ ISR

| State   | Mass [MeV]          | Width [MeV] | State   | Mass [MeV]          | Width [MeV] |
|---------|---------------------|-------------|---------|---------------------|-------------|
| Y(4080) | $4008 \pm 40^{+114}_{-28}$ | $226 \pm 44 \pm 87$ |         | -                   | -           |
| Y(4260) | $4247 \pm 12^{+17}_{-32}$  | $108 \pm 19 \pm 10$ |         | $4252 \pm 6^{+2}_{-3}$ | $105 \pm 18^{+4}_{-6}$ |
| Y(4360) | $4361 \pm 9 \pm 9$         | $74 \pm 15 \pm 10$ |         | $4324 \pm 24$       | $172 \pm 33$ |
| Y(4660) | $4664 \pm 11 \pm 5$         | $48 \pm 15 \pm 3$ |         | insignificant        | compatible  |

- Four states seen in $J/\psi \pi \pi$ or $\psi(2S)\pi \pi$
- Two of them only by Belle, not by Babar
- None corresponds to clear peak in $D(\ast)\overline{D}(\ast)$ cross section
- From production all must have $J^{PC} = 1^{--}$
- Not enough empty slots in conventional $c\bar{c}$ spectrum
Y(4140) → J/ψφ

→ In spring CDF announced evidence for resonance decaying to J/ψφ
→ Hidden strangeness in final state
\[ M \approx 4143.0 \text{ MeV}, \Gamma \approx 11.7 \text{ MeV} \]
BF=9.0 $\pm$ 3.4 $\pm$ 2.9 $\times$ 10$^{-6}$

Belle repeats search of CDF with \( B^+ \rightarrow J/ψφK^+ \) on full dataset
\[ B(B^+ \rightarrow Y(4140)K^+, Y \rightarrow J/ψφ) < 6 \times 10^{-6} @ 90\% \text{ C.L.} \]
$Y(4350) \rightarrow J/\psi \phi$

- Also search for $Y(4140) \rightarrow J/\psi \phi$ in $\gamma \gamma$ fusion
- Using 825 fb$^{-1}$ of Belle data
- No $Y(4140)$ signal, but low efficiency
- See another structure around 4350 MeV

- Properties:
  
  $M = 4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV
  
  $\Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1$ MeV

- Are we seeing another set of states corresponding to thresholds in $D_s$ system?

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Z^+(4430) \rightarrow \psi(2S)\pi^+

- Reanalysis of same data
- Confirm previous result
  \[ M = 4433^{+15}_{-12}{}^{+19}_{-13} \text{ MeV} \]
  \[ \Gamma = 107^{+86}_{-43}{}^{+74}_{-56} \text{ MeV} \]
- Lowest significance of 5.4\sigma
\[ Z^+(4430) \rightarrow \psi(2S)\pi^+ \]

- No significant signal seen
- Most significant peak has \(2.7\sigma\) at \(M = 4476 \pm 8\) MeV
- With \(K^*\) veto as in Belle analysis, peak at same position, but only \(1.9\sigma\)
\[ Z^+(4430) \rightarrow \psi(2S)\pi^+ \]

- Belle and Babar distributions consistent with each other
- None of the experiments can add significant amount of data
- Need other experiment or/and next generation B-factory
Belle studied $B^0 \to \chi_{c1}\pi^+K^-$ decays ($\chi_{c1} \to J/\psi\gamma$)
Clear signal for $\chi_{c1}$ and $B^0$: $N(B^0) = 2126 \pm 56 \pm 42$

- Study Dalitz plot
- Known resonances: $K^*(800), K^*(892), K^*(1440), K_0^*(1430), K_2^*(1430), K^*(1680), K_3^*(1780)$
- New resonances: two $Z^+(\pi^+\chi_{c1})$
$Z^+ \rightarrow \chi_{c1}\pi^+$

$1 < M^2(K\pi) < 1.75$ GeV

| MeV       | $Z(4050)$         | $Z(4250)$         |
|-----------|-------------------|-------------------|
| $M$       | $4051 \pm 14^{+29}_{-41}$ | $4248^{+44}_{-29}^{+180}_{-35}$ |
| $\Gamma$  | $82^{+21}_{-16}^{+47}_{-22}$ | $177^{+54}_{-39}^{+316}_{-61}$ |
| $\mathcal{B}_B \cdot \mathcal{B}_Z$ | $3.0^{+1.5}_{-0.8}^{+3.7}_{-1.6} \times 10^{-5}$ | $4.0^{+2.3}_{-0.9}^{+19.7}_{-0.5} \times 10^{-5}$ |

- Fit clearly prefers two new resonances
- Data favor two against one at $5.7\sigma$
- Spins not determined
- Large sys. uncertainties due to Dalitz model
- $\mathcal{B}$ comparable to $Z^+(4430), X(3872)$, ...

Only $K^*$ ($CL = 3 \times 10^{-10}$)

Incl. $Z^+$ ($CL = 42\%$)

$Z^+(4050)$

$Z^+(4250)$
Conclusions

- $X(3872)$ remains best studied state:
  - Tetraquark interpretation disfavored
  - Mass in $DD^*$ decays is consistent with $J/\psi \pi \pi$ decay at Belle

- $1^{--}$ sector remains overpopulated, but some states seen only by single experiment

- Three charged $Z$ states
  - All three come from Belle ($657M \, B\bar{B}$)
  - Babar searched for $Z(4430)$ with $1.9\sigma$ excess ($455M \, B\bar{B}$)

- Belle could not confirm or disprove $Y(4140)$ seen at CDF

- Still too many states in charmonium mass region for the conventional $c\bar{c}$ spectrum

- But many of low statistics and seen by single experiment
Exotic hadrons

**Conventional $c \bar{c}$:** Reasonably well understood mesons, known for long time. Number of states fixed with masses rather well predicted. Usually first choice for new state.

**Molecule:** Meson and antimeson loosely bound by pion exchange. Mass slightly below sum of mesons masses.

**Tetraquark:** Colored quarks tightly bound by gluon exchange. Expect charged states in charmonium mass region.

**Hybrids:** From LQCD $m > 4.2$ GeV, exotic $J^{PC}$ possible, large hadronic transitions $\psi \pi \pi$, $\psi \omega$. 
\[ Z^+(4430) \rightarrow \psi(2S)\pi^+ \]

- Study decay of \( B^0 \rightarrow \psi(2S)\pi^+K^- \)
- After \( K^* \) veto, observing resonance in \( \psi(2S)\pi^+ \)
  \[ M = 4433 \pm 4 \pm 1 \text{ MeV}, \quad \Gamma = 44^{+17}_{-13}^{+30}_{-11} \text{ MeV} \]
- Lot of interest because on non-zero charge \( \Rightarrow \) cannot be \( c\bar{c} \) meson