Study of exotic states in charmonium family at Belle

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Introduction

- Charmonium provides a unique possibility to check non-perturbative QCD models.
- Thanks to the large statistics collected at the B-factories (BaBar & Belle) many new charmonium(-like) particles were observed during the last decade.

### Theoretical models for exotic states:
- Molecule (2 loosely-bound charm mesons)
- Mixture of $c\bar{c}$ and molecule
- Tetraquark (tightly-bound 4-quark states)
- Hadrocharmonium ($c\bar{c}$ «coated» by light-hadron matter)
- Hybrid ($c\bar{c}$ with excited gluonic degrees of freedom)
- ...
Charmonium family

\[ \begin{array}{cccccccccc}
\psi(4415) & \psi(4040) & X(4160) & X(3940) & \eta_c(2S) & h_c & \chi_{c0} & \chi_{c1} & \chi_{c2} & Y(4660) \\
\psi(4360) & Y(4260) & Y(3915) & \chi_{c2}(2P) & X(3872) & \psi(3770) & Y(4008) & X(3820) & Z^+(4430) & Z^+(4250) \\
\end{array} \]
B $\rightarrow \chi_{c1,2} \gamma K$ (1)

Motivation:

- Observation of $X(3872) \rightarrow J/\psi \gamma$ confirmed $C = +1$.
- If $X(3872)$ is tetraquark or molecular state, there may by a C-odd partner decaying to $\chi_{c1} \gamma$ and $\chi_{c2} \gamma$.
- Undiscovered $c\bar{c}$ states $1^3D_2(\psi_2)$ and $1^3D_3(\psi_3)$ are expected to have significant branching fractions to $\chi_{c1} \gamma$ and $\chi_{c2} \gamma$.

Analysis features:

- $E_\gamma > 100$ MeV
- $\chi_{c1,2} \rightarrow J/\psi \gamma$ ($E_\gamma > 200$ MeV)
- $J/\psi \rightarrow l^+l^-$ ($l = e$ or $\mu$)
$B \rightarrow \chi_{c1,2} \gamma K$ (2)

$X(3823)$:

$M = 3823.1 \pm 1.8\text{(stat)} \pm 0.7\text{(syst)}$ MeV

$\Gamma < 24$ MeV (90% C.L.)

Near potential model expectations for $\psi_2(1^3D_2cc)$

$B \rightarrow \chi_{c1} \gamma K$
$B \rightarrow \chi_{c1,2} \gamma K$ (3)

$B \rightarrow \chi_{c2} \gamma K$

2.4σ peak $\Rightarrow$ not enough for an evidence!
$\mathbf{B \rightarrow \chi_{c1,2} \gamma K}$ (4)

<table>
<thead>
<tr>
<th>Decay</th>
<th>Yield ($Y$)</th>
<th>$S(\sigma)$</th>
<th>$\epsilon(%)$</th>
<th>Branching fraction $\mathcal{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \psi'(\rightarrow \chi_{cJ}\gamma)K^\mp$</td>
<td>193.2 ± 19.2</td>
<td>14.8</td>
<td>8.6</td>
<td>$7.7 \pm 0.8 \pm 0.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>59.1 ± 8.4</td>
<td>7.8</td>
<td>6.0</td>
<td>$6.3 \pm 0.9 \pm 0.6$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>50.3 ± 7.3</td>
<td>7.2</td>
<td>5.1</td>
<td>$6.8 \pm 1.0 \pm 0.7$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \psi'(\rightarrow \chi_{cJ}\gamma)K^0$</td>
<td>12.9 ± 4.4</td>
<td>2.9</td>
<td>3.5</td>
<td>$4.7 \pm 1.6 \pm 0.8$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>33.2 ± 9.7</td>
<td>3.8</td>
<td>10.9</td>
<td>$9.7 \pm 2.8 \pm 1.1$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>0.3 ± 3.9</td>
<td>0.1</td>
<td>8.8</td>
<td>$&lt;3.6$</td>
</tr>
<tr>
<td>$B^\pm \rightarrow X(3823)(\rightarrow \chi_{cJ}\gamma)K^\mp$</td>
<td>3.9 ± 3.4</td>
<td>1.2</td>
<td>6.0</td>
<td>$&lt;9.9$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>5.3 ± 2.9</td>
<td>2.4</td>
<td>5.0</td>
<td>$&lt;22.8$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>0.9 ± 5.1</td>
<td>11.1</td>
<td>11.1</td>
<td>$&lt;1.9$</td>
</tr>
<tr>
<td>$B^0 \rightarrow X(3823)(\rightarrow \chi_{cJ}\gamma)K^0$</td>
<td>4.7 ± 4.4</td>
<td>1.3</td>
<td>9.3</td>
<td>$&lt;6.7$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>4.6 ± 3.0</td>
<td>1.6</td>
<td>6.2</td>
<td>$&lt;9.6$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>2.3 ± 2.2</td>
<td>1.1</td>
<td>5.2</td>
<td>$&lt;12.2$</td>
</tr>
</tbody>
</table>

The production of C-odd partner of $X(3872)$ is suppressed

PRD 50, 4258 (1994)

E705 reported an indication (2.8σ) of $1^3D_2$ state with a mass of 3836 ± 13 MeV.
Search for $X(3872)$ decays to $\eta_c$ modes (1)

Motivation:
- $X(3872)$ was first observed by Belle in $B \rightarrow K(J/\psi \pi^+\pi^-)$. Angular analysis of this mode performed by LHCb determined all quantum numbers: $1^{++}$.
- If $X(3872)$ is a $D^0\bar{D}^*$ molecule, there may be other «X-like» particles with different quantum numbers, that are also bound states of $D^{(*)}$ mesons.
  - $X(3872)$: $(D^0\bar{D}^* - \bar{D}^0D^0)$ combination: $J^{PC}=1^{+-}$, decays $X \rightarrow \eta_c \omega$, $X \rightarrow \eta_c \rho$
  - $X(3730)$: $(D^0\bar{D}^0 + \bar{D}^0D^0)$ combination: $J^{PC}=0^{++}$, decays $X \rightarrow \eta_c \eta$, $X \rightarrow \eta_c \pi^0$
  - $X(4014)$: $(D^*\bar{D}^*0 + \bar{D}^*0D^0)$ combination: $J^{PC}=0^{++}$, decays $X \rightarrow \eta_c \eta$, $X \rightarrow \eta_c \pi^0$

Analysis features:
- $X$ is produced in charged B decays: $B^\pm \rightarrow K^\pm X$
- $\eta_c \rightarrow K_S K \pi$, $K_S \rightarrow \pi^+\pi^-$
- combined fit of 2 decay modes of $\eta$ ($\gamma\gamma$ and $\pi^+\pi^-\pi^0$)
- test mode $B^\pm \rightarrow K^\pm \psi(2S)$, $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ gives results consistent with PDG
- $B^\pm$ decays into the same final states, but without intermediate $X$ are studied
Search for $X(3872)$ decays to $\eta_c$ modes (2)

$B^\pm \to K^\pm X$

$X(3872)$

- $\eta_c \pi^+\pi^-$
- $\eta_c \omega$, $\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$
- $\eta_c \eta$
  - $\gamma\gamma$
- $X(3730)$
  - $\pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$
- $X(4014)$
  - $\eta_c \pi^0$, $\pi^0 \to \gamma\gamma$

$X(3872) \to \eta_c \pi^+\pi^-$

$X(3872) \to \eta_c \omega$

$X(3730) \to \eta_c \eta$

$X(3730) \to \eta_c \pi^0$

$X(4014) \to \eta_c \pi^0$

$\eta \to \gamma\gamma$

$\eta \to \pi^\pm \pi^0$

$X(4014) \to \eta_c \eta$

$\eta \to \gamma\gamma$
Search for $X(3872)$ decays to $\eta_c$ modes (3)

Preliminary results!

<table>
<thead>
<tr>
<th>$X$ mass, MeV/$c^2$</th>
<th>Decay mode</th>
<th>Yield</th>
<th>$U$ (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3872</td>
<td>$X \to \eta_c \pi^+ \pi^-$</td>
<td>$17.9 \pm 16.5$</td>
<td>$3.0 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$X \to \eta_c \omega$</td>
<td>$6.0 \pm 12.5$</td>
<td>$6.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>3730</td>
<td>$X \to \eta_c \eta, \eta \to \gamma \gamma$</td>
<td>$13.8 \pm 9.9$</td>
<td>$4.6 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$\eta \to \pi^+ \pi^- \pi^0$</td>
<td>$1.4 \pm 1.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X \to \eta_c \pi^0$</td>
<td>$-25.6 \pm 10.4$</td>
<td>$5.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>4014</td>
<td>$X \to \eta_c \eta, \eta \to \gamma \gamma$</td>
<td>$8.9 \pm 11.0$</td>
<td>$3.9 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$\eta \to \pi^+ \pi^- \pi^0$</td>
<td>$1.3 \pm 1.6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X \to \eta_c \pi^0$</td>
<td>$-8.1 \pm 13.2$</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Upper limits on the $\mathcal{B}(B^\pm \to K^\pm X) \cdot \mathcal{B}(X \to \eta_c h)$ for $h = \pi^+ \pi^-, \omega, \eta, \pi^0$

Upper limits on the $\mathcal{B}(B^\pm \to K^\pm \eta_c h)$ for $h = \pi^+ \pi^-, \omega, \eta, \pi^0$. 

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Yield</th>
<th>$U$ (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to K^\pm \eta_c \pi^+ \pi^-$</td>
<td>$155 \pm 72$</td>
<td>$3.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^\pm \to K^\pm \eta_c \omega$</td>
<td>$-41 \pm 27$</td>
<td>$5.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^\pm \to K^\pm \eta_c \eta, \eta \to \gamma \gamma$</td>
<td>$-14.1 \pm 26.1$</td>
<td>$2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$\eta \to \pi^+ \pi^- \pi^0$</td>
<td>$-1.8 \pm 3.4$</td>
</tr>
<tr>
<td></td>
<td>$B^\pm \to K^\pm \eta_c \pi^0$</td>
<td>$-1.9 \pm 12.1$</td>
</tr>
</tbody>
</table>
Motivation:
- $Y(4260)$ was observed by BaBar in $e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^- J/\psi$ (later confirmed by Belle).
- Belle (548 fb$^{-1}$) saw an excess of $\pi^+\pi^- J/\psi$ event production near 4 GeV — $Y(4008)$.
- BaBar (454 fb$^{-1}$) did not confirm $Y(4008)$.

Analysis features:
- cross section is measured between 3.8 and 5.5 GeV
- $|M^2_{\text{rec}}| < 2.0 \text{ GeV}^2$ for ISR
- $J/\psi \rightarrow l^+l^-$ ($l = e$ or $\mu$)
- measured $\psi(2S)$ production rate agrees with PDG
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (2)

Y(4260) parameters are consistent with previous results.

Y(4008) state is confirmed.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(R_1)$</td>
<td>3890.8 ± 40.5 ± 11.5</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R_1)$</td>
<td>254.5 ± 39.5 ± 13.6</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}B(R_1 \rightarrow \pi^+\pi^- J/\psi)$</td>
<td>(3.8 ± 0.6 ± 0.4)</td>
<td>(8.4 ± 1.2 ± 1.1)</td>
</tr>
<tr>
<td>$M(R_2)$</td>
<td>4258.6 ± 8.3 ± 12.1</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R_2)$</td>
<td>134.1 ± 16.4 ± 5.5</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}B(R_2 \rightarrow \pi^+\pi^- J/\psi)$</td>
<td>(6.4 ± 0.8 ± 0.6)</td>
<td>(20.5 ± 1.4 ± 2.0)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>59 ± 17 ± 11</td>
<td>−116 ± 6 ± 11</td>
</tr>
</tbody>
</table>
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (3)

$Z(3900)^\pm$

$M = 3894.5 \pm 6.6({\text{stat}}) \pm 4.5({\text{syst}})$ MeV

$\Gamma = 63 \pm 24({\text{stat}}) \pm 26({\text{syst}})$ MeV

Significance $> 5.2\sigma$

Interference between S and D waves in $\pi^+\pi^-$ cannot produce this peak.

Charged + strong coupling to $c\bar{c}$ $\Rightarrow$ not a conventional charmonium!
$e^+e^- \rightarrow \eta J/\psi$ (1)

Motivation:
- In the vector sector above 4.0 GeV there are 3 excited $\psi$ ($\psi(4040)$, $\psi(4160)$, $\psi(4415)$) + 4 exotic $c\bar{c}$ ($Y(4008)$, $Y(4260)$, $Y(4360)$, $Y(4660)$) = 7 states
- Potential models predict only 5 charmonia in this mass region.
- $\psi$ states are identified in decays to charmed meson pairs but not in dipion transitions to lower $\psi$. The opposite is true for $Y$ states.

Cross section $e^+e^- \rightarrow \eta J/\psi$

Analysis features:
- cross section is measured between 3.8 and 5.3 GeV
- $-1 < M^2_{\text{rec}} < 2.0 \text{ GeV}^2$ for ISR
- $\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+\pi^-\pi^0$
- $J/\psi \rightarrow l^+l^-$ ($l = e$ or $\mu$)
- measured $\psi(2S)$ production rate agrees with PDG
$e^+e^- \rightarrow \eta J/\psi$ (2)

Masses and width of these two peaks are consistent with $\psi(4040)$ and $\psi(4160)$, so they are fixed to corresponding PDG values.

The minimal statistical significance is $6.0\sigma$ for $\psi(4040)$ and $6.5\sigma$ for $\psi(4160)$.

Two possible solutions for the interference phase give different $\mathcal{B} \cdot \Gamma_{ee}^\psi$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\psi(4040)}$</td>
<td>$4039$ (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\psi(4040)}$</td>
<td>$80$ (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{\psi(4040)}$</td>
<td>$4.8 \pm 0.9 \pm 1.5$</td>
<td>$11.2 \pm 1.3 \pm 2.1$</td>
</tr>
<tr>
<td>$M_{\psi(4160)}$</td>
<td>$4153$ (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\psi(4160)}$</td>
<td>$103$ (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{\psi(4160)}$</td>
<td>$4.0 \pm 0.8 \pm 1.4$</td>
<td>$13.8 \pm 1.3 \pm 2.1$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$336 \pm 12 \pm 14$</td>
<td>$251 \pm 4 \pm 7$</td>
</tr>
</tbody>
</table>
Taking $\Gamma_{\psi ee}$ from PDG:

$$B(\psi(4040) \to \eta J/\psi) = (0.56 \pm 0.10\text{(stat)} \pm 0.18\text{(syst)})\% \quad \text{(solution I)}$$
$$\quad (1.30 \pm 0.15\text{(stat)} \pm 0.26\text{(syst)})\% \quad \text{(solution II)}$$

$$B(\psi(4160) \to \eta J/\psi) = (0.48 \pm 0.10\text{(stat)} \pm 0.18\text{(syst)})\% \quad \text{(solution I)}$$
$$\quad (1.66 \pm 0.16\text{(stat)} \pm 0.29\text{(syst)})\% \quad \text{(solution II)}$$

Transition rates are ~1 MeV.

**Upper limits** at 90% C.L. on $B(X \to \eta J/\psi) \cdot \Gamma_{\psi ee}^X$ for

- $X = Y(4260) \quad 14.2$ eV
- $X = Y(4360) \quad 6.8$ eV
- $X = \psi(4415) \quad 3.6$ eV
- $X = Y(4660) \quad 0.94$ eV
Summary

- **First evidence** of a narrow state $X(3823)$ that decays to $\chi_{c1}\gamma$ has been found. Its properties are consistent with those expected for the $\psi_2(1^3D_2\bar{c}\bar{c})$ state.
- Upper limit was set on the production of the $X(3872)$'s C-odd partner in 2-body B-decays and its decay to $\chi_{c1,2}\gamma$.
- Search for decays of different «$X(3872)$-like» particles to $\eta_c \pi^+ \pi^-$, $\eta_c \omega$, $\eta_c \eta$, and $\eta_c \pi^0$ was performed. Upper limits were set on the corresponding product branching fractions $\mathcal{B}(B^\pm \rightarrow K^\pm X) \times \mathcal{B}(X \rightarrow \eta_c \ldots)$.
- The cross section of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ has been measured from 3.8 to 5.5 GeV.
- $Y(4260)$ is observed and its resonant parameters are determined in the decay to $\pi^+\pi^-J/\psi$. $Y(4008)$ state is confirmed.
- A new charged $cc$-like state $Z(3900)^\pm$ is observed in $\pi^+J/\psi$ (also confirmed by BESIII and T. Xiao et al. using CLEO data).
- The cross section of $e^+e^- \rightarrow \eta J/\psi$ has been measured from 3.8 to 5.3 GeV.
- For the first time $\psi(4040)$ and $\psi(4160)$ are observed in decays to **final states without charm meson pairs**.