EXOTIC/CHARMONIUM HADRON SPECTROSCOPY AT BELLE AND BABAR

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On behalf of Belle collaboration
Rencontres de Moriond
QCD and High Energy Interactions
La Thuile, March 20–27, 2011

- Belle experiment;
- Overview of exotic/charmonium spectroscopy;
- $\eta_c$ & $\eta_c(2S')$ properties;
- $X(3872)$ radiative decays;
- $\omega J/\psi$ final state study;
- Search for $(c\bar{c})$ in $\Upsilon(1S')$ radiative decays;
- Summary.

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Belle at KEKB

<table>
<thead>
<tr>
<th>$\Upsilon$ Decays</th>
<th>Belle</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(5S)$</td>
<td>121 fb$^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>$\Upsilon(4S)$</td>
<td>711 fb$^{-1}$</td>
<td>433 fb$^{-1}$</td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>3.0 fb$^{-1}$</td>
<td>30 fb$^{-1}$</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>24 fb$^{-1}$</td>
<td>14 fb$^{-1}$</td>
</tr>
<tr>
<td>$\Upsilon(1S)$</td>
<td>5.7 fb$^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>Off-resonance</td>
<td>87 fb$^{-1}$</td>
<td>54 fb$^{-1}$</td>
</tr>
<tr>
<td>Scan</td>
<td>68 fb$^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>1020 fb$^{-1}$</td>
<td>531 fb$^{-1}$</td>
</tr>
</tbody>
</table>
Overview of exotic/charmonium spectroscopy

- First \((c\bar{c})\) state \(J/\psi\) was discovered in 1974;
- In 1974–1980 nine more \((c\bar{c})\) states were observed: \(\psi(2S), \eta_c, \chi_{c0}, \chi_{c1}, \chi_{c2}, \psi(3770), \psi(4040), \psi(4160)\) and \(\psi(4415)\);
- No new \((c\bar{c})\) states between 1980 and 2002;
- In 2002 Belle found \(\eta_c(2S)\);
- In 2003 Belle discovered \(X(3872)\), first “exotic charmonium-like” state;
- Since then a bunch of new states was found.

<table>
<thead>
<tr>
<th>State</th>
<th>(M), MeV</th>
<th>(\Gamma), MeV</th>
<th>(J^{PC})</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_c(1P))</td>
<td>3525.45 ± 0.15</td>
<td>0.73 ± 0.53</td>
<td>1(^+)−</td>
<td>(\psi(2S) \rightarrow \pi^0(\gamma \eta_c))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt; 1.44)</td>
<td></td>
<td>(\psi(2S) \rightarrow \pi^0(\gamma \ldots))</td>
</tr>
<tr>
<td>(\eta_c(2S))</td>
<td>3637 ± 4</td>
<td>14 ± 7</td>
<td>0(^−)+</td>
<td>(p\bar{p} \rightarrow (\gamma \eta_c) \rightarrow (\gamma \gamma \gamma))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\psi(2S) \rightarrow \pi^0(\ldots))</td>
</tr>
<tr>
<td>(\chi_{c2}(2P)) ((Z(3930)))</td>
<td>3927.2 ± 2.6</td>
<td>24.1 ± 6.1</td>
<td>2(^++)</td>
<td>(B \rightarrow K(K_S^0 K^- \pi^+))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\gamma \gamma \rightarrow (K_S^0 K^- \pi^+))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(e^+ e^- \rightarrow J/\psi (\ldots))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\gamma \gamma \rightarrow (D \bar{D}))</td>
</tr>
</tbody>
</table>

## Overview of exotic/charmonium spectroscopy (2)

<table>
<thead>
<tr>
<th>State</th>
<th>$M$, MeV</th>
<th>$\Gamma$, MeV</th>
<th>$J^{PC}$</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.52 ± 0.20</td>
<td>1.3 ± 0.6</td>
<td>1$^{++}$/2$^{--}$</td>
<td>$B \rightarrow K(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt; 2.2)</td>
<td></td>
<td>$p\bar{p} \rightarrow (\pi^+\pi^- J/\psi) + ...$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\omega J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(D^* D^0)$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\gamma J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\gamma(2S))$</td>
</tr>
<tr>
<td>$X(3915)$</td>
<td>3915.6 ± 3.1</td>
<td>28 ± 10</td>
<td>0/2$^+$</td>
<td>$B \rightarrow K(\omega J/\psi)$</td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>$3942^{+9}_{-8}$</td>
<td>$37^{+27}_{-17}$</td>
<td>$?$+$</td>
<td>$e^+ e^- \rightarrow J/\psi(D\bar{D}^*)$</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+ e^- \rightarrow J/\psi (\ldots)$</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>$4008^{+121}_{-49}$</td>
<td>226 ± 97</td>
<td>1$^-$</td>
<td>$e^+ e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td>$Z_1(4050)^+$</td>
<td>$4051^{+24}_{-43}$</td>
<td>$82^{+51}_{-55}$</td>
<td>$?$</td>
<td>$B \rightarrow K(\pi^+ \chi_{c1}(1P))$</td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4143.4 ± 3.0</td>
<td>15$^{+11}_{-7}$</td>
<td>$?$+$</td>
<td>$B \rightarrow K(\phi J/\psi)$</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>$4156^{+29}_{-25}$</td>
<td>$139^{+113}_{-65}$</td>
<td>$?$+$</td>
<td>$e^+ e^- \rightarrow J/\psi(D\bar{D}^*)$</td>
</tr>
<tr>
<td>$Z_2(4250)^+$</td>
<td>$4248^{+185}_{-45}$</td>
<td>$177^{+321}_{-72}$</td>
<td>$?$</td>
<td>$B \rightarrow K(\pi^+ \chi_{c1}(1P))$</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4263 ± 5</td>
<td>108 ± 14</td>
<td>1$^-$</td>
<td>$e^+ e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+ e^- \rightarrow (\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+ e^- \rightarrow (\pi^0\pi^0 J/\psi)$</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4353 ± 11</td>
<td>96 ± 42</td>
<td>1$^-$</td>
<td>$e^+ e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td>$Z(4430)^+$</td>
<td>$4443^{+24}_{-18}$</td>
<td>$107^{+113}_{-71}$</td>
<td>$?$</td>
<td>$B \rightarrow K(\pi^+ \psi(2S))$</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>$4634^{+9}_{-11}$</td>
<td>$92^{+41}_{-32}$</td>
<td>1$^-$</td>
<td>$e^+ e^- \rightarrow \gamma(\Lambda_c^+ \Lambda_c^-)$</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1$^-$</td>
<td>$e^+ e^- \rightarrow \gamma(\pi^+\pi^- \psi(2S))$</td>
</tr>
</tbody>
</table>
Overview of exotic/charmonium spectroscopy (3)

- B-factories
- Spectroscopy overview
  - \( \eta_c \) & \( \eta_c(2S) \) properties
  - X(3872)
  - \( \omega J/\psi \)
  - Charmonium in \( \Upsilon(1S) \) decays
- Summary
- Backup

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Dmitri Liventsev – ITEP, Moscow – Moriond QCD’11

Exotic/charmonium hadron spectroscopy at Belle and BaBar – 5 / 22
Charmonium production at B-factories

In 2-body decays in factorization limit:

\[ J^{PC} = 0^{-+}, 1^{--}, 1^{++} \]

Double charmonium production

\[ C = +1 \]

2γ production

\[ J^{PC} = 0^{±+}, 2^{±+} \]

Initial State Radiation (ISR)

\[ J^{PC} = 1^{--} \]
Exotic charmonium-like states

- **Tetraquark**: four tightly bound quarks
- **Molecular state**: two loosely bound mesons
- **Hybrid**: states with excited gluonic degrees of freedom
- **Hadrocharmonium**: charmonium state, “coated” by excited light-hadron matter

**Exotics signature**:

- $J^{PC}$, forbidden for charmonium
- Extremely narrow width for a state above $D \bar{D}$
- Non-zero charge, strangeness
There is a large spread in $\eta_c$ mass and width measurements.

$\Gamma(\eta_c) \simeq 15\text{ MeV}$ in $J/\psi$ and $\psi'$ radiative decays

$\Gamma(\eta_c) \simeq 30\text{ MeV}$ in $B$-decays
$\eta_c$ & $\eta_c(2S)$ new mass measurement: BaBar

BaBar:
$\gamma\gamma \rightarrow \eta_c \rightarrow K_SK\pi$ is the “right place” for $M$ and $\Gamma$ determination.

$\eta_c$ mass is measured relative to $J/\psi$.
$\sim 500 / fb$

$M_{\eta_c} = 2982.2 \pm 0.4 \pm 0.6 \text{ MeV}$,
$\Gamma_{\eta_c} = 31.7 \pm 1.2 \pm 0.8 \text{ MeV}$.

$M_{\eta_c(2S)} = 3638.3 \pm 1.5 \pm 0.6 \text{ MeV}$,
$\Gamma_{\eta_c(2S)} = 14.2 \pm 4.4 \pm 2.5 \text{ MeV}$.

Transition form factor in $\gamma\gamma \rightarrow \eta_c$ was measured.

Nice agreement with pQCD.
$\eta_c$ & $\eta_c(2S)$ new mass measurement: Belle

Belle: interference is important!

$B^+ \rightarrow K^+(K_SK\pi)^0$

Interference with non-res. $B^+ \rightarrow K^+(K_SK\pi)^0$.

2D fit: $\angle(K^+, K_S) - M(K_SK\pi)$.

$M_{\eta_c} = 2985.4 \pm 1.5^{+0.2}_{-2.0}$ MeV

$\Gamma_{\eta_c} = 35.1 \pm 3.1^{+1.0}_{-1.6}$ MeV

$M_{\eta_c(2S)} = 3636.1^{+3.9}_{-4.1} +0.5$ MeV

$\Gamma_{\eta_c(2S)} = 6.6^{+8.4}_{-5.1} +2.6_{-0.9}$ MeV

No interference:

$\Gamma_{\eta_c(2S)} = 41.1 \pm 12.0^{+6.4}_{-10.9}$ MeV

Significant effect for $\eta_c(2S)$ width!
Study of $\eta_c(2S)$ decays: Belle

- Only one exclusive mode was known $K_SK\pi$ until recently.
- Not seen in 4-prong final state (Belle EPJC53, 1 (2008)).
- Belle studied $\gamma\gamma \rightarrow \eta_c(2S) \rightarrow$ 6-prong with 923 /fb.
- 6-prong: $6\pi$, $2K4\pi$, $4K2\pi$, $K_SK3\pi$.

Results for $\eta_c(2S)$:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$M$, MeV</th>
<th>$\Gamma$, MeV</th>
<th>Signif.</th>
<th>$\Gamma_{\gamma\gamma}B$, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6\pi$</td>
<td>3638.9 ± 1.6 ± 2.3</td>
<td>10.7 ± 4.9</td>
<td>8.5$\sigma$</td>
<td>20.1 ± 3.7 ± 3.2</td>
</tr>
<tr>
<td>$2K4\pi$</td>
<td>3634.7 ± 1.6 ± 2.8</td>
<td>&lt; 13 @ 90$%$CL</td>
<td>6.2$\sigma$</td>
<td>10.2 ± 2.3 ± 3.4</td>
</tr>
<tr>
<td>$K_SK3\pi$</td>
<td>3636.5 ± 1.8 ± 2.4</td>
<td>15.9 ± 5.7</td>
<td>8.7$\sigma$</td>
<td>30.7 ± 3.9 ± 3.7</td>
</tr>
</tbody>
</table>

$M(\eta_c(2S)) = 3636.9 \pm 1.1 \pm 2.5 \pm 5.0$ MeV (possible interference with background)

$\Gamma(\eta_c(2S)) = 9.9 \pm 3.2 \pm 2.6 \pm 2.0$ MeV

Dmitri Liventsev – ITEP, Moscow – Moriond QCD’11

Belle, ICHEP’10
Study of $\eta_c(2S)$ decays: BaBar

$\sim 500 /fb$

First observation of $\eta_c$, $\chi_{c0}$, $\chi_{c2}$ and $\eta_c(2S)$ decays to $K^+ K^- \pi^+ \pi^- \pi^0$.

$$\frac{\mathcal{B}(\eta_c \rightarrow K^+ K^- \pi^+ \pi^- \pi^0)}{\mathcal{B}(\eta_c \rightarrow (K_S K \pi)^0)} = 1.42 \pm 0.06 \pm 0.26,$$

$$\frac{\mathcal{B}(\eta_c(2S) \rightarrow K^+ K^- \pi^+ \pi^- \pi^0)}{\mathcal{B}(\eta_c(2S) \rightarrow (K_S K \pi)^0)} = 2.1 \pm 0.4 \pm 0.5.$$
Discovered by Belle in $B^\pm \to J/\psi \pi^+ \pi^- K^\pm$ decays. Confirmed by D0, CDF, BaBar. What do we know about it?

$M(X) - (m_{D^0} + m_{D^{*0}}) = -0.32 \pm 0.35$ MeV

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

$M(\pi^+ \pi^-)$ is consistent with $\rho \Rightarrow$

large isospin violation;

$C = +1$.

$X(3872) \to \pi^+ \pi^- \pi^0 J/\psi \Rightarrow$

$M(\pi^+ \pi^- \pi^0)$ is consistent with $\omega$,

different isospin then $\rho J/\psi$.

Angular analysis: $J^{PC} = 1^{++}$ or $2^{-+}$

$S$-wave $D^0 \bar{D}^{*0}$ molecular state?

E.S.Swanson, PLB 588, 189 (2004)
Evidence for $X(3872) \rightarrow J/\psi \gamma$ by Belle with 256 /fb
13.6 ± 4.4 events
Proof of $C = +$
Confirmed by BaBar

Recently BaBar measured with 424 /fb

$N(X \rightarrow J/\psi \gamma) = 23.0 \pm 6.4 \ (3.6\sigma)$

$\mathcal{B}(B^+ \rightarrow K^+ X) \times \mathcal{B}(X \rightarrow J/\psi \gamma) = (2.8 \pm 0.8) \times 10^{-6}$

Belle reported with 711 /fb

$N_{B^+}(X \rightarrow J/\psi \gamma) = 30.0^{+8.2}_{-7.4}$

$N_{B^0}(X \rightarrow J/\psi \gamma) = 5.7^{+3.5}_{-2.8}$

4.9\sigma (2.4\sigma)

$\mathcal{B}(B^+ \rightarrow K^+ X) \times \mathcal{B}(X \rightarrow J/\psi \gamma) = (1.8 \pm 0.5) \times 10^{-6}$
Recently BaBar reported with 424 /fb evidence for $X \rightarrow \psi'\gamma$

$$N(X \rightarrow \psi'\gamma) = 25.4 \pm 7.3$$

$$\frac{B(X \rightarrow \psi'\gamma)}{B(X \rightarrow J/\psi\gamma)} = 3.4 \pm 1.4$$

Ratio is too large for molecule? (Swanson PLB598, 197 (2004))

Belle searched for $X \rightarrow \psi'\gamma$ with 711 /fb

Broad peaking background from $B \rightarrow \psi' K(*)$

$$N_{B^+}(X \rightarrow \psi'\gamma) = 5.0^{+11.9}_{-11.0}$$

$$N_{B^0}(X \rightarrow \psi'\gamma) = 1.5^{+4.8}_{-3.9}$$

$$\frac{B(X \rightarrow \psi'\gamma)}{B(X \rightarrow J/\psi\gamma)} < 2.0 \text{ @90}\%\text{CL}$$
Study of $\omega J/\psi$ final state

Three charmonium-like states with masses close to 3940 MeV were discovered:
- $X(3940): e^+e^- \rightarrow J/\psi D\bar{D}$
- $Y(3940): B \rightarrow K\omega J/\psi$
- $Z(3930): \gamma\gamma \rightarrow D\bar{D}$

Belle studied $\gamma\gamma \rightarrow \omega J/\psi$ with 694 /fb
$M(X(3915)) = 3915 \pm 3 \pm 2$ MeV
$\Gamma(X(3915)) = 17 \pm 10 \pm 3$ MeV

Assumption $X(3915) = Y(3940)$ is compatible with data.

If $X(3915) = Z(3930) = \chi'_{c2}$

$$\frac{B(\chi'_{c2} \rightarrow \omega J/\psi)}{B(\chi'_{c2} \rightarrow D\bar{D})} > 0.08$$

Huge for charmonium above open charm threshold.
Study of $\omega J/\psi$ final state (2)

Evidence for $X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi$ through sub threshold $X \rightarrow \omega J/\psi$ was reported by Belle

Looser requirement on $\pi\pi\pi^0$ inv. mass: moved to 0.74 GeV.
Both $X(3872)$ and $Y(3940)$ were observed. Masses and widths are consistent with previous measurements.

$M(\pi^+ \pi^- \pi^0)$ distribution favours $P$-wave ($J^P = 2^-$):
\[
\chi^2/\text{NDF} = 10.17/5 \text{ for } S\text{-wave},
\]
\[
\chi^2/\text{NDF} = 3.53/5 \text{ for } P\text{-wave}.
\]

Is it conventional $(c\bar{c}) - \eta_c(2S)$?
Interference between $X$ and $Y$?

$X \rightarrow D\bar{D}\pi$ is a challenge!

(Y. Kalashnikova, arXiv:1008.2895)
Search for charmonium in $\Upsilon(1S)$ radiative decays

Belle also studied

$$(b\bar{b}) \rightarrow (c\bar{c})\gamma$$ process

5.7 /fb in $\Upsilon(1S)$

and 1.8 /fb in continuum

ISR removed

$\chi_{cJ} \rightarrow \gamma J/\psi$ 

$\eta_c \rightarrow$ 5 hadronic modes

No evidence for excited charmonium states below 4.8 GeV.

<table>
<thead>
<tr>
<th>State ($R$)</th>
<th>$B(10^{-5})$</th>
<th>Theor.</th>
<th>UL (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0}$</td>
<td>3</td>
<td>&lt; 65</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>1</td>
<td>&lt; 2.3</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>0.6</td>
<td>&lt; 0.76</td>
<td></td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>5</td>
<td>&lt; 5.7</td>
<td></td>
</tr>
<tr>
<td>$X(3872) \rightarrow \pi\pi J/\psi$</td>
<td></td>
<td>&lt; 0.16</td>
<td></td>
</tr>
<tr>
<td>$X(3872) \rightarrow \pi\pi^0 J/\psi$</td>
<td></td>
<td>&lt; 0.28</td>
<td></td>
</tr>
<tr>
<td>$X(3915) \rightarrow \omega J/\psi$</td>
<td></td>
<td>&lt; 0.30</td>
<td></td>
</tr>
<tr>
<td>$Y(4140) \rightarrow \phi J/\psi$</td>
<td></td>
<td>&lt; 0.22</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- New precise measurements of masses and widths of $\eta_c$ and $\eta_c(2S)$ with interference effects taken into account;
- Nature of $X(3872)$, first observed “exotic” state, is still not clear;
- $X(3872) \rightarrow \omega J/\psi$ confirmed;
- No $(c\bar{c})$ states observed in $\Upsilon(1S)$ radiative decays.

$B$-factories have made surprising discoveries of new states but we need more study and larger data samples to reveal the true nature of these states.
$e^+ e^- \rightarrow J/\psi (D \bar{D}^*)$

$357 / fb$

$M = 3943 \pm 6 \text{ MeV}$

$\Gamma = 15.4 \pm 10.1 \text{ MeV}$

$5.0 \sigma$

$B \rightarrow K (\omega J/\psi)$

$253 / fb$

$M = 3943 \pm 11 \pm 13 \text{ MeV}$

$\Gamma = 87 \pm 22 \pm 26 \text{ MeV}$

$8.1 \sigma$

$\gamma \gamma \rightarrow D \bar{D}$

$395 / fb$

$M = 3929 \pm 5 \pm 2 \text{ MeV}$

$\Gamma = 29 \pm 10 \pm 2 \text{ MeV}$

$5.3 \sigma$
KEK has established earthquake emergency response team (head: Director General) on 11 March in response to the occurrence of the biggest earthquake ever Japan has experienced in our history. All accelerators and experimental devices were stopped the operation immediately after the first shake. We have confirmed the radiation safety, and no hazard to the environment has been reported. Also there are no reports of casualties on both Tsukuba and Tokai campuses.