Charmonium and –like states from Belle

QCD Moriond 2012
Vishal Bhardwaj, Nara
(on behalf of the Belle collaboration)
Outline

• Charmonium searches at Belle

• Search for narrow resonance in $B \rightarrow J/\Psi \eta K$

• Search for narrow resonance in $B \rightarrow \chi_{c1} \gamma K$

• Results and Conclusion
In this talk

Production of $c\bar{c}$ (-like) in B-factory

A few % of B mesons decay into $c\bar{c}$ and $K^{(*)}$

Easy to study.
Low background.

$J^{PC}$ using angular studies.

Double Charmonium

Clean and ideal place to carry charmonium spectroscopy related business.
Analysis procedure

Reconstruct $B^\pm$ (of interest)

Common variable used in analyses

\[
M_{bc} = \sqrt{E_{beam}^2 - p_B^2}
\]

\[
\Delta E = E_B - E_{beam}
\]

$M_{J/\psi \pi\pi}$ or $M_{\text{final state of interest}}$

To identify background, large sample of $B \rightarrow J/\Psi \ X$ (final state, here $X$ can be anything) MC is used.
General purpose detector, build to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\psi, \Psi', \chi_{c1}, K^0$).

Contribution to charmonium (-like) states:
- $\eta_c(2S)$, $X(3872)$, $Y(3940)$, $Z(3930)$, $X(3940)$, $X(3915)$, $Y(4260)$, $Y(4660)$, $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$ ...
**X(3872)**  Most famous $c\bar{c}$ (-like) state

Discovered by Belle in $J/\psi \pi \pi$ decay mode

- $M_{ll\pi\pi} - M_{ll}$ (GeV/c$^2$)
- $B^+ \rightarrow X(3872) K^+$,
- $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
- $\Gamma < 2.5$ MeV (90%CL)
- $p p \rightarrow X(3872)$ any

Difficult to assign to a conventional charmonium state.

Confirmed by CDF, DO, BaBar, CMS and LHCb.
Update on properties of $X(3872)$

Belle, PRD 85,052004 (2011)

Mass diff. b/w charged and neutral B decay is
$\Delta M_{X(3872)} = (-0.69 \pm 0.97 \pm 0.19) \text{ MeV}$

$M_{X(3872)} = (3871.84 \pm 0.27 \pm 0.19) \text{ MeV}$

$\Gamma_{X(3872)} < 1.2 \text{ MeV (90\% C.L.)}$

Prediction: $\Delta M(M_{X(B^+)} - M_{X(B^0)}) = (8 \pm 3) \text{ MeV}$

Mass diff. b/w charged and neutral B decay is
$\Delta M_{X(3872)} = (-0.69 \pm 0.97 \pm 0.19) \text{ MeV}$

Maiani et al., PRD71, 014028(2005)

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

$J^{PC}$ through angular analysis
- $1^{++}$
- $2^+$ a free complex parameter; one value gives an acceptable fit

$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow J/\psi\pi\pi) = (8.61 \pm 0.82 \pm 0.52) \times 10^{-6}$
**X(3872)$^+$ existence ?**

Tetraquark model predicts the existence of isospin triplet : $X(3872)^+$

- $B^0 \to X(3872)^+K^-$
- $B^+ \to X(3872)^+K^0$

**Br(\text{B}^+ \to X(3872)^+K^0) = 2 \times \text{Br}(\text{B}^0 \to X(3872)K^0)**

- Reconstruct $X(3872)^+ \to J/\psi \pi^+\pi^0$
- No signal is seen
- UL (@90% CL) is provided

$\text{Br}(B^0 \to X^+K^-) \times \text{Br}(X^+ \to \pi^+\pi^0J/\psi) < 3.9 \times 10^{-6}$

**No charged partner**

$\text{Br}(B^+ \to X^+K^0) \times \text{Br}(X^+ \to \pi^+\pi^0J/\psi) < 4.5 \times 10^{-6}$

Rule out isospin triplet model ?

Few tetraquark models predict $X(3872)^+$ to be broad, non-observed yet because of low statistics (?).

If $X(3872)$ is tetraquark, than $X(3872)$ has C-odd partner which can dominantly decay into

- $X(3872)^C \to J/\psi \eta$
- $X(3872)^C \to \chi_{c1}\gamma$

K. Terasaki, arXiv : 1107.5868v2
Search for $X(3872)^{c-}$ in $J/\Psi \eta$

No signal was seen in $X(3872)$ region.

$$\mathcal{B}R(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}R(X(3872) \rightarrow J/\Psi \eta) < 7.7 \times 10^{-6} \ (90\% \ CL)$$

BaBar observed $B^+ \rightarrow J/\Psi \eta K^+$ and provided

$$\mathcal{B}R(B^+ \rightarrow J/\Psi \eta K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$$

With more data (9x), Belle can either rule out or put much tighter constraint on the $X(3872)^{c-}$ partner.
Search for $X(3872)^{c-}$ in $M_{J/\psi\eta}$

No signal was seen in $X(3872)$ region.

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Above 3.9 GeV, some hint of new states?

Additional motivation

“Search for new state in $M_{J/\psi\eta}$”
**B^\pm \rightarrow J/\Psi \eta K^\pm** Analysis

To reduce background
- \psi' \rightarrow J/\Psi \pi\pi veto
- \pi^0 veto

Select events in the -35 MeV < \Delta E < 30 MeV and look for the \(M_{J/\Psi \eta}\) distribution.

**BaBar got 50.3\pm3.0 event for \(B \rightarrow J/\Psi \eta K\) in \Delta E distribution.**

**Large signal (428\pm37 events) of \(B \rightarrow J/\Psi \eta K\) in \Delta E distribution.**

**BaBar, PRL 93, 041801 (2004)**
After including phase space (PHSP) component of $B \to J/\Psi \eta K$, data/MC agrees quite well.

1D UML fit to $M_{J/\Psi \eta}$ in order to extract signal yield.

Background fixed from MC and sideband study.
Results of $B^\pm \to J/\Psi \eta K^\pm$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Events</th>
<th>$BR$ ($10^{-4}$)</th>
<th>Belle</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to \Psi' K^+$</td>
<td>52±8.2</td>
<td>5.81±0.92±0.44</td>
<td>6.39 ± 0.33</td>
<td></td>
</tr>
<tr>
<td>$B^+ \to J/\Psi \eta K^+$</td>
<td>395±26</td>
<td>1.17±0.07±0.11</td>
<td>1.08 ± 0.33(2)</td>
<td></td>
</tr>
</tbody>
</table>

Our results agree with the world average.

In the search of $X(3872) \to J/\Psi \eta$, Belle provided upper limit (@90% CL)

(1) Belle’s $BR(B \to \Psi'(\to J/\Psi \eta) K$, while the world average is for $BR(B \to \Psi'(\to \eta) K$ & $BR(B \to \Psi'(\to J/\Psi \pi \pi) K$

(2) includes $B \to \Psi'(\to J/\Psi \eta) K$ component also. Belle $BR$ is for the PHSP component.
Results of $B^\pm \to J/\Psi \eta K^\pm$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Events</th>
<th>$\text{BR}(B^+ \to X K^+) \cdot \text{BR}(X \to J/\Psi \eta)$ (10$^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to X(3872)(\to J/\Psi \eta) K^+$</td>
<td>2.3±5.2</td>
<td>Belle: 2.3±5.2, PDG: &lt;3.8, Preliminary: &lt;7.7</td>
</tr>
</tbody>
</table>

UL (@90% CL) is also provided at different masses (using 0-width states).

Much tighter constraint to the C-odd partner of $X(3872)$. 

- UL (@90% CL)
Search for $X(3872)^{c-}$ in $\chi_{c1}\gamma$

- In previous search of $X(3872)\rightarrow\chi_{c1}\gamma$, no signal was seen.

- Theory predicts $^3D_2$ $c\bar{c}$ state to lie around $\sim3810$-$3840$ MeV/$c^2$ mass and should be narrow.

- $\Gamma(\psi_2\rightarrow\chi_{c1}\gamma) = 260$ keV.

- With current statistics, we expect to find some hint of $\Psi_2$ or other C-odd resonance.

Search for new exotic state in $\chi_{c1}\gamma$ by scanning $M_{\chi_{c1}\gamma}$ (mass distribution) for narrow peak.
\[ B^{\pm} \rightarrow \chi_{c1} \gamma K^{\pm} \] Analysis

Reconstruct \( B^{\pm} \) (of interest)

To reduce background
- \( \pi^0 \) veto
- \( \chi_{c1}' \gamma \) veto

\[-28 \text{ MeV} < \Delta E < 30 \text{ MeV}\]

\( E_\gamma \) scaled (\( \Delta E=0 \)) to improve the resolution of \( M_{\chi_{c1}\gamma} \)

- 2D UML fit to \( M_{\chi_{c1}\gamma} \) & \( M_{bc} \) extract signal yield
- If some new resonance, it will become visible in \( M_{\chi_{c1}\gamma} \) in \( M_{bc} \) signal region.

MC for illustration purpose

Projection in signal region
Narrow peak observed around 3820 MeV/c$^2$.

No strong evidence for any discrepancy between data/MC, except this narrow peak.

$M_{\chi c_1 \gamma}$ distribution

$M_{bc} > 5.27$ GeV/c$^2$

$B^+ \rightarrow \psi(\rightarrow \chi_{c1} \gamma) K^+$

$B^+ \rightarrow \Psi(\rightarrow \chi_{c1} \gamma) K^+$

Combinatorial background
Mass of new peak

\[ \text{B}^+ \rightarrow \chi_{c1} \gamma K^+ \]

Peak at \[ 3823.5 \pm 2.8 \text{ MeV/c}^2 \]

Yield: \[ 4.2\sigma \text{ (syst. Included)} \]

\[ 33.2 \pm 9.1 \]

Clear evidence of signal at 3823 MeV/c²

\[ M_{\chi_{c1}\gamma} \text{ (GeV/c}^2) \]

\[ M_{bc} \text{ (GeV/c}^2) \]

- \( \Psi'_2 \) width fixed to zero, resolution scaled from MC
- For more details, please see backup.

Projection in signal region

- \( M_{bc} > 5.27 \text{ GeV/c}^2 \)
- \( 3.66 < M_{\chi_{c1}\gamma} < 3.708 \text{ GeV/c}^2 \)
- \( 3.805 < M_{\chi_{c1}\gamma} < 3.845 \text{ GeV/c}^2 \)

2D UML

Peaking background

\( B \rightarrow \Psi \kappa^*, \chi_{c1} K^*, \Psi K\pi, \chi_{c1} K\pi, \ldots \)
What is this peak?

Ψ₂ below D Górski* threshold: expected to have narrow decay width of 300-400 keV

Ψ₂ → D Górski is forbidden due to parity
Mostly decaying into χ₁c₁γ.

3D₂ mass is quite near and the observed peak has not been seen in D Górski (3D₂ → D Górski is expected).

X(3823) seems to be the missing Ψ₂ from the charmonium spectrum.

$B^\pm \rightarrow \chi_{c1}\gamma K^\pm$  

**NEW**

$X(3872)^{C-}$

**711 fb$^{-1}$**

**Preliminary**

$X(3872)$ yield : $-0.9 \pm 5.1$ events

**Projection**

No hint of $X(3872)$

**No signal is observed in the $X(3872)$ region.**

$B.R.(B^\pm \rightarrow X(3872)K^\pm) \times B.R.(X(3872) \rightarrow \chi_{c1}\gamma) < 2.0 \times 10^{-6}$ (@90% CL)

\[
\frac{\Gamma(X(3872)\rightarrow \chi_{c1}\gamma)}{\Gamma(X(3872)\rightarrow J/\Psi\pi\pi)} < 0.26
\]

PRD 85,052004 (R) (2011)

* Recent Belle result used for BR($B \rightarrow X(3872)K$)*BR($X(3872) \rightarrow J/\Psi\pi^+\pi^-$).
Fit results

<table>
<thead>
<tr>
<th>( B^\pm \rightarrow \chi_{c1}\gamma K^\pm )</th>
<th>Yield</th>
<th>( BR(B^+ \rightarrow X K^+). BR(X \rightarrow \chi_{c1}\gamma) \times 10^{-6} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Psi_2 \rightarrow \chi_{c1}\gamma )</td>
<td>33.2±9.1</td>
<td>9.70^{+2.84}_{-2.51}(stat) ± 1.1(syst)</td>
</tr>
<tr>
<td>( X(3872) \rightarrow \chi_{c1}\gamma )</td>
<td>-0.9±5.1</td>
<td>&lt; 2.0(@90% CL)</td>
</tr>
</tbody>
</table>

\( BR(B^+ \rightarrow \Psi' K^+) = (7.74\pm0.8\pm0.9) \times 10^{-4} \) is consistent with PDG.

First evidence of \( \Psi_2 \) with 4.2 \( \sigma \) significance by Belle.

\[
\frac{\Gamma(X(3872) \rightarrow \chi_{c1}\gamma)}{\Gamma(X(3872) \rightarrow J/\psi\pi\pi)} < 0.26
\]

Much tighter constraint to the C-odd partner of \( X(3872) \).
Results & Conclusion

First evidence of narrow state at 3823 MeV in $\chi_{c1}\gamma$.
- Most probably the missing $\Psi_2(c\bar{c})$ state.

$X(3872)$ as tetraquark
- No signal seen in tetraquark interpretation of $X(3872)$ in J/$\Psi\eta$, $\chi_{c1}\gamma$.
- Most stringent upper limits are provided (0 width hypothesis).

$X(3872)$ properties update.
- Precise $X(3872)$ mass and best limit on width (<1.2 MeV @ 90%C.L)
- Precise branching fractions in B decays ($B \rightarrow X(3872)K$)
- No charged partner found.
- $J^{PC}$ (1$^{++}$ or 2$^{-+}$)

Further scope
- Confirmation of $\Psi_2$ at other experiments.
  Interesting to compare it with predicted $BR(\Psi_2 \rightarrow J/\Psi\pi\pi)$, can be measured at LHC.
- $\Psi_2 \rightarrow \chi_{c2}\gamma$ or search for another resonance.
- $X(3872) \rightarrow J/\Psi\pi^+\pi^-\pi^0$ update with 3 times more data.
- $X(3872) \rightarrow \eta_c\pi^+\pi^-$ search.
Thank you
Welcome to the Backup Wizard

This wizard helps in keeping track of BACK-UP slides

To continue press Next >
Discrepancy can be explained by the phase space (PHSP) component of $B \to J/\psi \eta K$. 

$B^+ \to \psi' K^+$

$B^+ \to J/\psi \eta K^+ (PHSP)$
Looking at $\psi'$, here 3.836 peaks looks prominent ???

A search has been made in 300 GeV/c $\pi^{\pm}$ - and proton-Li interactions for production of states that decay into $J/\psi$ or $\psi'$ plus one or two pions. A 2.5$\sigma$ enhancement in the $J/\psi \pi^0$ spectrum, possibly the recently reported $^1P_1$ state of charmonium, is observed at a mass of 3.527 GeV/$c^2$. In the $J/\psi$ plus two pion mass spectrum, we report, together with the expected $\psi' \to J/\psi \pi^+ \pi^-$, the tentative observation of a structure at a mass of 3.836 GeV/$c^2$. No enhancements are seen in the $J/\psi \pi^\pm \pi^\pm$, $J/\psi \pi^\pm \pi^0$, $J/\psi \pi^\pm$, or $\psi' \pi^\pm$ mass spectra.

PhysRevD.50.4258
Interestingly $\Psi_2$ is not seen in $J/\Psi \pi \pi$ in other experiments.
<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>$\psi'$</th>
<th>$\psi_2$</th>
<th>X3872</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{BB}$</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
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<tr>
<td>Tracking</td>
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<td>1.6</td>
<td>1.6</td>
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<tr>
<td>Efficiency</td>
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<td>0.4</td>
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<tr>
<td>Kaon id</td>
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<tr>
<td>Lepton id</td>
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<td>3.6</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>$\gamma$ id</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>$\pi^0$ veto</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Secondary B.R.</td>
<td>6.1</td>
<td>4.4</td>
<td>4.4</td>
<td></td>
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<tr>
<td>PDFs</td>
<td>+7.3</td>
<td>+7.9</td>
<td>+7.9</td>
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</tr>
<tr>
<td></td>
<td>-6.4</td>
<td>-7.5</td>
<td>-7.5</td>
<td></td>
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<tr>
<td>Fit bias</td>
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<td>2.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+11.3</td>
<td>+10.9</td>
<td>+11.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-10.7</td>
<td>-10.6</td>
<td>-10.8</td>
<td></td>
</tr>
</tbody>
</table>

$B^\pm \rightarrow \chi_{c1} \gamma K^\pm$
-198 < ΔE < -140 MeV
100 < ΔE < 158 MeV

ΔE sideband

2 x signal region

B^± → χ_{c1}γK^±

No unexpected peaking background is seen.

B → J/ψ X MC agrees quite well with data.
There is a small bump around 3950 MeV/c^2 due to γ of χ_{c1} combining with fake χ_{c1}. In order to remove this bump, we need to use χ_{c1}’ γ veto.
Signal extraction in $M_{\chi c_1\gamma}$

Background parameterized using large $B\to J/\Psi X$ MC sample

For fit bias, 2000 toys and no significant bias is observed. Maximum bias of 2% estimated and included in the systematics.

*Estimated from signal MC (for different width)
Radiative decays of $X(3872)$

Belle found evidence for $X(3872) \to J/\psi \gamma$ in $B^+ \to X(3872) K^+$ with $+ve$ C parity

Also seen by BaBar

$$\mathcal{BR}(B^+ \to XK^+) \cdot \mathcal{BR}(X \to J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

PRL 102, 132001 (2009)

Also find $X(3872) \to \psi' \gamma$

$$\frac{\mathcal{BR}(X(3872) \to \psi' \gamma)}{\mathcal{BR}(X(3872) \to J/\psi \gamma)} = 3.5 \pm 1.4$$

Update from Belle establish $X(3872) \to J/\psi \gamma$ with 5.5σ observation*

$$\mathcal{BR}(B^+ \to XK^+) \times \mathcal{BR}(X \to J/\psi \gamma) = (1.78 \pm 0.46 \pm 0.12) \times 10^{-6}$$

However, Belle didn’t saw any signal in $X(3872) \to \psi' \gamma$

$$\frac{BR(X \to \psi' \gamma)}{BR(X \to J/\psi \gamma)} < 2.1 \,(\text{@90\% CL})$$

* combining $B^+ \to X K^+$ & $B^0 \to X K^0$

* combining $B^+ \to X K^+$ & $B^0 \to X K^0$
$X(3872)$ mass (in $\pi^+\pi^-J/\psi$ channel only)

World Average ($J/\psi\pi\pi$): $3871.67 \pm 0.17$ MeV/c$^2$

$M_{X(3872)} - (M_{D^0} + M_{\bar{D}^*0}) = -0.12 \pm 0.35$ MeV/c$^2$

S. Olsen talk’s
The fit to the angles suggest $J^{PC}$ of $X(3872)$:

- $1^{++}$
- $2^+$ (for certain choices of $B_{11}/B_{12}$ [for $(L,S) = (1,1)$ or $(1,2)$])

Angle b/w $J/\psi$ and direction opposite to $K$ in $X(3872)$ frame.

Angle b/w $\pi^+$ and direction opposite to $K$ in $X(3872)$ frame.

Angle b/w $l^+$ and direction opposite to $K$ in $X(3872)$ frame.

Belle, Phys. Rev. D 84, 052004 (2011)
\(M_{\pi\pi}\) study for \(X(3872)\)

Earlier Belle analysis of \(M_{\pi\pi}\) favored S-wave \(\rho\omega\)

So, \(J^{PC} = 1^{++}\)

CDF included Blatt-Weisskopf factors and \(\rho-\omega\) interference \(\rightarrow\) rendered P-wave fit equally good

Recent Belle analysis with and without \(\rho-\omega\) suggest \(2^+\) as well.

\[
\begin{array}{c|c|c|c}
 L & \chi^2/n_{dof} & \rho\omega \text{ fit to final data} & \rho\omega \text{ fit to final data} \\
 \hline
 0 \text{ (dashed)} & 17.5/18 & \text{without } \rho-\omega \text{ int:} & \text{with } \rho-\omega \text{ int:} \\
 1 \text{ (solid)} & 32.1/18 & L & \chi^2/n_{dof} \\
 0 \text{ (dashed)} & 15.8/17 & 1 \text{ (solid)} & 14.6/17 \\
 \end{array}
\]