Radiative Transitions above 4 GeV at BESIII

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(For the BESIII Collaboration)

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Radiative transitions and $Y(4260)$

• Many unconventional charmonium-like (so-called XYZ) states were discovered, e.g. $X(3872)$, $Y(4260)$, $Y(4360)$..., while the nature of the states remains unclear.

• $Y(4260)$ was observed in ISR process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$ by BaBar, which has $J^{PC} = 1^{--}$ and can be directly produced in $e^+e^-$ collisions;

• The $Y(4260)$ is heavier than DD threshold, but mostly decays to $\pi^+\pi^-J/\psi$;

• There’s no place for $Y(4260)$ in the conventional charmonium family;

• The newly observed $Z_c$ particles seem to couple with $Y(4260)$. 

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Radiative transitions and $Y(4260)$

- To better understand the nature of $Y(4260)$, it’s important to investigate the radiative transitions between the $Y(4260)$ and the lower mass charmonium(-like) states (e.g. $X(3872), \chi_{cJ}$).

- Search for new C-even charmonium(-like) states (e.g. $Y(4140), Y(3915)$) via radiative transitions.

- The $e^+e^-$ collider BEPCII can reach 4.6 GeV for now, so we can produce $Y(4260)$ directly.
Radiative transitions

1. Observation of $e^+e^- \rightarrow \gamma X(3872)$ (RPL 112,092001)
2. Search for $e^+e^- \rightarrow \gamma Y(4140)$ (PRD 91,032002)
3. Search for $e^+e^- \rightarrow \gamma \chi_{cJ}$ (CPC, 39(4) (2015) 041001)

The results in the talk are based on 4 energy points

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<tbody>
<tr>
<td>0.5 fb⁻¹</td>
<td>$\psi(4040)$</td>
<td>at 4.09 GeV</td>
</tr>
<tr>
<td>1.9 fb⁻¹</td>
<td>$Y(4260)$</td>
<td>at 4.23 and 4.26 GeV</td>
</tr>
<tr>
<td>0.5 fb⁻¹</td>
<td>$Y(4360)$</td>
<td>at 4.36 GeV</td>
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</table>
The feature of $X(3872)$

- **Discovered** by Belle in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ in 2003, and confirmed by many other experiments;
- very narrow ($< 1.2$ MeV);
- BaBar and Belle observed $X(3872) \rightarrow \gamma J/\psi$, ensuring $X(3872)$ C-even state;
- Spin parity $J^P = 1^+$ (CDF and LHCb);
- Very close to $D \bar{D}^*$ threshold, a good candidate for a hadronic molecule or a tetraquark state;
- Only observed in B meson decays and hadron collisions; radiative transition at BESIII?
Observation of $e^+e^- \rightarrow \gamma X(3872)$ via $X(3872) \rightarrow \pi^+\pi^-J/\psi$

- **Observe** $e^+e^- \rightarrow \gamma X(3872)$ for the first time with a significance $6.3\sigma$.

- **Measured mass** is $M(X(3872)) = (3871.9 \pm 0.7 \pm 0.2)$ MeV/c$^2$, agrees with previous measurements well.

- **Measured** $\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \times B[X(3872) \rightarrow \pi^+\pi^-J/\psi]$ at 4.009, 4.23, 4.26, 4.36 GeV.

- These results suggest that $X(3872)$ may come from $Y(4260)$ decay. Assuming $B[X(3872) \rightarrow \pi^+\pi^-J/\psi]=5\%$, $\frac{B(Y(4260)\rightarrow \gamma X(3872))}{B(Y(4260)\rightarrow \pi^+\pi^-J/\psi)} \approx 0.1$
Search for $Y(4140)$ via $e^+e^- \rightarrow \gamma \phi J/\psi$

**Exist**

*CDF* first reported evidence for $Y(4140)$ in $B^+ \rightarrow \phi J/\psi K^+$; CDFII claimed observation ($>5\sigma$)

*CMS* and *D0* studied $B^+ \rightarrow \phi J/\psi K^+$; with resonance parameters consistent with CDF

**or not?**

*Belle* did not confirm $Y(4140)$ in the $B^+ \rightarrow \phi J/\psi K^+$ and $\gamma\gamma \rightarrow \phi J/\psi$

*LHCb* did not find $Y(4140)$ in $B^+ \rightarrow \phi J/\psi K^+$

*BABAR* found no evidence for $Y(4140)$ by study $B^+ \rightarrow \phi J/\psi K^+$
Search for $Y(4140)$ via $e^+e^- \rightarrow \gamma \phi J/\psi$

- The mass and width of $Y(4140)$ given by CDFII are $4143.4 \pm 3.1$ MeV/$c^2$ and $15.3 \pm 10.7$ MeV;
- $Y(4140)$ is not a conventional charmonium state, but a good candidate for $D_s^*\overline{D}_s^*$ molecular state;
- Both $\phi$ and $J/\psi$ have $J^{PC} = 1^{--}$, the $Y(4140)$ has positive C-parity and can be searched for through radiative transition of $Y(4260)$.

$e^+e^- \rightarrow \gamma \phi J/\psi, J/\psi \rightarrow e^+e^-/\mu^+\mu^-$

- 1. $\phi \rightarrow K^+K^-$ (one Kaon is missing),
- 2. $\phi \rightarrow K_SK_L$ ($K_L$ is missing),
- 3. $\phi \rightarrow \pi^+\pi^-\pi^0$
\[ \phi \to K^+ K^- \]
\[ \phi \to K_S^0 K_L^0 \]
\[ \phi \to \pi^+ \pi^- \pi^0 \]

\[ \sqrt{s} = 4.23 \text{ GeV} \]
\[ \sqrt{s} = 4.26 \text{ GeV} \]
\[ \sqrt{s} = 4.36 \text{ GeV} \]
Combine 6 modes (3 Φ modes × 2 J/ψ modes)

$\sqrt{s} = 4.23 \text{ GeV}$

$\sigma^B \cdot \mathcal{B} < 0.35 \text{ pb}$

$\sqrt{s} = 4.26 \text{ GeV}$

$\sigma^B \cdot \mathcal{B} < 0.28 \text{ pb}$

$\sqrt{s} = 4.36 \text{ GeV}$

$\sigma^B \cdot \mathcal{B} < 0.33 \text{ pb}$

Sum of all data sets

Three events seem like Y(4140).
No background from MC studies.

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No significant $Y(4140)$ signal found

- Upper limit at the 90% C.L. for
  \[ \sigma^B \times B = \sigma^B(e^+e^- \rightarrow \gamma Y(4140)) \times B(Y(4140) \rightarrow \phi J/\psi) \]

<table>
<thead>
<tr>
<th>(\sqrt{s}) (GeV/c(^2))</th>
<th>Luminosity (pb(^{-1}))</th>
<th>((1 + \delta))</th>
<th>(\sigma^B \times B) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.23</td>
<td>1094</td>
<td>0.840</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>4.26</td>
<td>827</td>
<td>0.847</td>
<td>&lt;0.28</td>
</tr>
<tr>
<td>4.36</td>
<td>545</td>
<td>0.944</td>
<td>&lt;0.33</td>
</tr>
</tbody>
</table>

*Systematic uncertainty included*

- Compared with the $X(3872)$ production (same magnitude)
  \[ \sigma^B(e^+e^- \rightarrow \gamma X(3872)) \times B(X(3872) \rightarrow \pi^+\pi^- J/\psi) \]
  \[ = 0.27 \pm 0.09\) (stat) \(\pm 0.02\) (syst) pb at \(\sqrt{s} = 4.23\) GeV,
  \[ = 0.33 \pm 0.12\) (stat) \(\pm 0.02\) (syst) pb at \(\sqrt{s} = 4.26\) GeV.

- Take \(B(X(3872) \rightarrow \pi^+\pi^- J/\psi) = 5\%\). [arXiv: 0910.3138](https://arxiv.org/abs/0910.3138)
  And \(B(Y(4140) \rightarrow \phi J/\psi) = 30\%\), molecular calculation. [PRD 80, 054019](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.80.054019).

\[ \frac{\sigma(e^+e^- \rightarrow \gamma Y(4140))}{\sigma(e^+e^- \rightarrow \gamma X(3872))} \leq 0.1 \text{ at } \sqrt{s}=4.23 \text{ and } 4.26 \text{ GeV.} \]
Search for $e^+ e^- \rightarrow \gamma \chi_{cJ}$ at $\sqrt{s} > 4$ GeV

- The cross sections of $e^+ e^- \rightarrow \gamma \chi_{cJ}$ have been evaluated theoretically with the framework of NRQCD;
- In experiment, CLEO investigated the process but failed to observe a signal;
- BESIII has collected large data sample for deeply investigate the processes, which may provide more information on the properties of $Y(4260)$.

- The process is reconstructed by
  
  $$ e^+ e^- \rightarrow \gamma \chi_{cJ} \rightarrow \gamma J/\psi \rightarrow \mu^+ \mu^- $$
Search for $e^+e^- \rightarrow \gamma \chi_{cJ}$ at $\sqrt{s} > 4$ GeV

Unbinned likelihood fit to $M(\gamma J/\psi)$

**Signal:** a double-Gaussian determined from MC at 4.260 GeV;

**Background:** radiative dimuon MC shape;

**Data:** limited statistics
Search for $e^+e^- \rightarrow \gamma \chi_{cJ}$ at $\sqrt{s} > 4$ GeV

The results on $e^+e^- \rightarrow \gamma \chi_{cJ}$ born cross section measurement

<table>
<thead>
<tr>
<th>$\sqrt{s}$/GeV</th>
<th>$N^{\text{obs}}$</th>
<th>significance ($\sigma$)</th>
<th>$N^{\text{UP}}$</th>
<th>$\sigma^{\text{UP}}$/pb</th>
<th>$\sigma^{\text{B}}$/pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.009</td>
<td>Xc0: 7.0±6.6</td>
<td>1.6</td>
<td>18</td>
<td>179</td>
<td>65.0±61.3±4.2</td>
</tr>
<tr>
<td></td>
<td>Xc1: 4.4±2.6</td>
<td>2.2</td>
<td>9</td>
<td>5.3</td>
<td>2.4±1.4±0.2</td>
</tr>
<tr>
<td></td>
<td>Xc2: 1.8±1.7</td>
<td>1.5</td>
<td>6</td>
<td>18</td>
<td>4.7±4.4±0.6</td>
</tr>
<tr>
<td>4.230</td>
<td>Xc0: 0.2±2.3</td>
<td>0.0</td>
<td>7</td>
<td>26</td>
<td>0.7±8.0±0.1</td>
</tr>
<tr>
<td></td>
<td>Xc1: 4.7±4.3</td>
<td>1.9</td>
<td>14</td>
<td>1.7</td>
<td>0.7±0.5±0.1</td>
</tr>
<tr>
<td></td>
<td>Xc2: 13.3±5.2</td>
<td>2.9</td>
<td>22</td>
<td>5.0</td>
<td>2.7±1.1±0.3</td>
</tr>
<tr>
<td>4.260</td>
<td>Xc0: 0.1±1.9</td>
<td>0.0</td>
<td>5</td>
<td>25</td>
<td>0.5±8.8±0.1</td>
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<tr>
<td></td>
<td>Xc1: 3.0±3.0</td>
<td>1.1</td>
<td>7</td>
<td>1.1</td>
<td>0.4±0.4±0.1</td>
</tr>
<tr>
<td></td>
<td>Xc2: 7.5±3.9</td>
<td>2.3</td>
<td>14</td>
<td>4.2</td>
<td>2.0±1.1±0.2</td>
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<tr>
<td>4.360</td>
<td>Xc0: 0.1±0.7</td>
<td>0.0</td>
<td>3</td>
<td>23</td>
<td>0.7±5.0±0.1</td>
</tr>
<tr>
<td></td>
<td>Xc1: 5.2±4.9</td>
<td>2.4</td>
<td>10</td>
<td>2.9</td>
<td>1.4±1.3±0.1</td>
</tr>
<tr>
<td></td>
<td>Xc2: 4.4±4.5</td>
<td>2.0</td>
<td>9</td>
<td>5.0</td>
<td>2.3±2.3±0.2</td>
</tr>
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</table>

- Significance $\sigma$ is small due to limited statistics;
- The upper limits on $\sigma^B$ are compatible with the theoretical prediction;
- The first uncertainty of $\sigma^B$ is statistical, and the second systematic.

arXiv:1310.8597
Evidence for $e^+ e^- \rightarrow \gamma \chi_{c1}/\chi_{c2}$

Fit to the sum of $M(\gamma J/\psi)$ distribution of the 4 energy points

A simultaneous fit to $M(\gamma J/\psi)$ at 4 energy points with assuming the production $\sigma(e^+ e^- \rightarrow \gamma \chi_{cJ})$ at different $\sqrt{s}$ follows the lineshape of $Y(4260)$

The statistical significances for $\chi_{c0}, \chi_{c1}, \chi_{c2}$ are $1.2\sigma, 3.0\sigma, 3.4\sigma$ respectively.

The statistical significances for $\chi_{c0}, \chi_{c1}, \chi_{c2}$ are $0, 2.4\sigma, 4.0\sigma$ respectively.
Summary

• Transition $e^+ e^- \rightarrow \gamma X(3872)$ at $\sqrt{s} > 4$ GeV is observed with significance $6.3\sigma$, perhaps via $Y(4260) \rightarrow \gamma X(3872)$.

• The $Y(4140)$ is searched via $e^+ e^- \rightarrow \gamma \phi J/\psi$, no evidence is found (three events).

• The evidence for $e^+ e^- \rightarrow \gamma \chi_{c1}/\chi_{c2}$ at $\sqrt{s} > 4$ GeV is found.

• We are still analyzing the data; more interesting results are expected.

Thank you!