Perspectives on spectroscopy study at Belle II

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on behalf of the Belle II collaboration

Quarkonium 2017 @ Peking University, 6-10 Nov 2017
Spectroscopy of heavy quarkonia

- Heavy quarkonium: bound states of $c\bar{c}$ or $b\bar{b}$
  - Treated with NRQCD due to the heavy $c/b$ mass
  - Tests of perturbative and non-perturbative QCD
- B-factories did great job in establishing the long awaited states and finding surprises in exotic quarkonium-like states

![Diagram showing mass vs. $J^{PC}$ for $c\bar{c}$ and $b\bar{b}$ systems before and after B-factories.]

6/11/17
Belle @ KEKB → Belle II @ SuperKEKB

- 40 times increase in luminosity!
  - $2.1 \times 10^{34} \rightarrow 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.
- $E(e^-) \ 7.0 \ \text{GeV, } E(e^+) \ 4.0 \ \text{GeV}$
- Targeted $L_{int} = 50 \ \text{ab}^{-1}$. (Belle $\sim 1\text{ab}^{-1}$)
Belle II detector

More info & status: YE Hua’s talk “Status of Belle II and SuperKEKB”

- Better vertexing; Improved PID capability; Fast data-acquisition...
Bottomonia(-like)
Total cross-section above BB threshold have been measured in $\Upsilon(nS)\pi\pi$ and $B_S(\ast)\bar{B}_S(\ast)$

- $R_b$ dip vs. $\Upsilon\pi\pi$ bump
- Sign of $\Upsilon_b$ states?

Expected study:
$BB, BB^*, B^*B^*(\pi), \Upsilon\pi\pi, \Upsilon\eta$, especially at 10.65, 10.75 GeV.

\[ R_b = \frac{\sigma(ee\rightarrow\text{hadron})}{\sigma_{\mu\mu}} \]

\[ R_{\Upsilon\pi\pi} = \frac{\sigma_{\Upsilon\pi\pi}}{\sigma_{\mu\mu}} \]


PRD 93, 011101(R) (2016)
Zb in Υ(6S)

- Charged Zb⁺ state is observed in Υ(5S) → π[πΥ]/π[πhb]
- Evidence of Υ(6S) → π⁺π⁻hb(nP), via Zb(10610) or Zb(10650)
- Statistics is not large enough to distinguish contributions from the two states

More data needed for this FS and other possibilities:
- Υ(6S) → π⁺π⁻Υ(mS), π⁺π⁻hb(nP)
- With π⁰π⁰

6/11/17
**Z\(_b\) in \(\Upsilon(6S)\)**

- \(Z_b(10610)\) and \(Z_b(10650)\) also found in \(B\bar{B}^*\) and \(B^*\bar{B}^*\) final states, respectively.

- For molecular bottomonia interpretation, \(Z_b\) has neutral partners \(W_b\).

- Potential searches:
  - \(\Upsilon(6S) \rightarrow \gamma W_b\)
  - \(\Upsilon(6S) \rightarrow \pi^+\pi^- W_b/\rho W_b\)
  - \(W_b \rightarrow \eta_b\pi, \chi_b\pi, \Upsilon\rho\)

Voloshin, PRD 84, 031502 (R)
Hadronic transition of Y(5S) and Y(6S)

- For bottomonium states above BB threshold, hadronic transitions suppressed by Heavy Quark Spin Symmetry are enhanced.

- Could be explained if the Y states are not pure $b\bar{b}$ but a “molecular” admixture of meson pairs.

<table>
<thead>
<tr>
<th>State</th>
<th>Decomposition into $b\bar{b}$ spin eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BB$</td>
<td>$\frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01}$</td>
</tr>
<tr>
<td>$BB^*$</td>
<td>$\frac{1}{\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12}$</td>
</tr>
<tr>
<td>$(B^<em>\bar{B}^</em>)_{S=0}$</td>
<td>$-\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01}$</td>
</tr>
<tr>
<td>$(B^<em>\bar{B}^</em>)_{S=2}$</td>
<td>$\frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spin eigenstate</th>
<th>Expected decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_{10}$</td>
<td>$\Upsilon(nS)\pi^+\pi^-$, $\Upsilon(nS)K^+K^-$ in $S$ wave</td>
</tr>
<tr>
<td>$\psi_{11}$</td>
<td>$\Upsilon(nS)\eta$, $\Upsilon(nS)\eta'$</td>
</tr>
<tr>
<td>$\psi_{11}$, $\psi_{12}$</td>
<td>$\Upsilon(nS)\pi^+\pi^-$, $\Upsilon(nS)K^+K^-$ in $D$ wave</td>
</tr>
<tr>
<td>$\psi_{01}$</td>
<td>$\eta_b(nS)\omega$, $\eta_b(nS)\phi$, $h_b(nP)\eta$, $h_b(nP)\eta'$</td>
</tr>
</tbody>
</table>
Missing $b\bar{b}$ states below $B\bar{B}$ threshold

Y(6S) data at 11.02 GeV will open the door to some unestablished bottomonium states

- $\Upsilon(6S) \rightarrow \pi\pi h_b(3P)$
- $\Upsilon(6S) \rightarrow \pi\pi \Upsilon(2D)/ \eta \Upsilon(2D)$
- 1F triplet 2,3,4++ may be from 2D transition
- $\Upsilon(1D), \Upsilon(2D)$ can be searched in direct scan
Resolving $Y(1D)$ triplet in $Y(3S)$ decays

- $Y(1D)$ produced in $Y(3S)$ radiative decay
  - Followed by dipion decay to $Y(1S)$
  - Four-gamma cascade

Yield per $10^9$ $Y(3S)$ decays
- $2.4 \times 10^3 \, ^3D_1$
- $19 \times 10^3 \, ^3D_2$
- $6.8 \times 10^3 \, ^3D_3$

Godfrey and Moats, PRD 92, 054034 (2015)

BaBar, PRD 82, 111102 (2010)

CLEO, PRD 82, 111102 (2010)
Planned data-points

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scans Off. Res.</th>
<th>$\Upsilon(6S)$ fb$^{-1}$</th>
<th>$\Upsilon(5S)$ fb$^{-1}$</th>
<th>$\Upsilon(4S)$ fb$^{-1}$</th>
<th>$\Upsilon(3S)$ fb$^{-1}$</th>
<th>$\Upsilon(2S)$ fb$^{-1}$</th>
<th>$\Upsilon(1S)$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>17.1</td>
<td>-</td>
<td>0.1</td>
<td>16</td>
<td>17.1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>BaBar</td>
<td>54</td>
<td>$R_b$ scan</td>
<td>433</td>
<td>471</td>
<td>30</td>
<td>122</td>
<td>14</td>
</tr>
<tr>
<td>Belle</td>
<td>100</td>
<td>$\sim 5.5$</td>
<td>36</td>
<td>121</td>
<td>711</td>
<td>772</td>
<td>3</td>
</tr>
</tbody>
</table>

- **Above BB threshold**
  - Detailed $Z_b$ study at $\Upsilon(6S) \sim 20$/fb
  - Hadronic transition
  - Scan at higher energy (up to 11.24 GeV $\Lambda_b\bar{\Lambda}_b$ threshold)

- **Below BB threshold**
  - 200~300 /fb at $\Upsilon(3S)$
  - Scan of $\Upsilon(1D)$ and $\Upsilon(2D)$ regions

6/11/17
Production:

In B decays

Direct production/ISR

Photon production

Double charmonia production

Charmonium(-like) states
Charmonium-like exotics from B decays

- Amplitude analysis can be performed in B decays, thus the quantum number of exotic states could be determined.
- With larger data sample, spin-parity of other exotic states is to be determined, especially for those observed in a single final state:
  - $\chi(3915)$ in $B \to K \omega J/\psi$ (also interesting for $\chi(3872)$!)
  - $Z_c(4050), Z_c(4250)$ in $B \to K \pi X_{c1}$
- Search for open flavour decays, esp. for candidates of molecules
  - $B \to KD\bar{D}, KD^*\bar{D}, KD^*\bar{D}^*$
Charmonia in B decay – absolute BF

- Absolute BF of exotic states can be measured in $B \rightarrow KX$ via the missing mass recoiling against the kaon.
- Initial momentum of the mother $B$ can be determined by fully reconstructing the accompany $\bar{B}$

Unique at $ee$ collider!

Belle, arXiv:1709.06108

BaBar, PRL 96, 052002 (2006)
ISR

- Coverage of the full energy spectrum (line shape, fine structure...);
- Many simultaneous $\sqrt{s}$, point-to-point systematics small
- Lower efficiency (boost may help)

vs. direct production

- Higher luminosity at fixed $\sqrt{s}$;
- Better resolution;
- Much higher efficiency

- Belle II can do ISR studies in
  - Charmonium + light hadrons
  - Charm meson pair (+light hadrons)
Charged $Z_c$ search:
- Evidence of $Z_c(4050)$ found in $Y(4360) \rightarrow \pi^+\pi^-\psi(2S)$, needs confirmation

ISR production of charmonium + light hadrons in addition to $\pi\pi\psi$:
- $\gamma X(3872)$; $\psi(4040), \psi(4160)$ into $\eta J/\psi, KK\psi$, ...
- Charm meson pairs: $D \bar{D}, D \bar{D}^*(\pi)$, ...

PRD 91, 112007 (2015)
Golden channels of ISR

<table>
<thead>
<tr>
<th>Golden Channels</th>
<th>$E_{c.m.}$ (GeV)</th>
<th>Statistical error (%)</th>
<th>Related XYZ states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^- J/\psi$</td>
<td>4.23</td>
<td>7.5 (3.0)</td>
<td>Y(4008), Y(4260), $Z_c(3900)$</td>
</tr>
<tr>
<td>$\pi^+\pi^- (2S)$</td>
<td>4.36</td>
<td>12 (5.0)</td>
<td>Y(4260), Y(4360), Y(4660), $Z_c(4050)$</td>
</tr>
<tr>
<td>$K^+K^- J/\psi$</td>
<td>4.53</td>
<td>15 (6.5)</td>
<td>$Z_c$</td>
</tr>
<tr>
<td>$\pi^+\pi^- h_c$</td>
<td>4.23</td>
<td>15 (6.5)</td>
<td>Y(4220), Y(4390), $Z_c(4020)$, $Z_c(4025)$</td>
</tr>
<tr>
<td>$\omega\chi_{c0}$</td>
<td>4.23</td>
<td>35 (15)</td>
<td>Y(4220)</td>
</tr>
</tbody>
</table>

10 ab$^{-1}$ by 2020 (50 ab$^{-1}$ by 2024)

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$:
- Line shape around 4.26 GeV?
  Confirm Y(4008)?
- Detailed study of charged $Z_c(3900)$
With 10/ab the statistical uncertainty already competitive

Dedicated ISR generator PHOKHARA has been implemented in Belle II framework

BESIII, PRL 118, 092001 (2017)
Double charmonium production

- \( e^+e^- \rightarrow J/\psi X, X = c\bar{c} \)
  - X can be studied using \( J/\psi \) recoil, especially for \( C \)-even states
  - X = conventional \( c\bar{c} \), \( \eta_c \) \((1S, 2S)\); or = exotics: \( X(3940), X(4160), X^*(3860) \)...
  - Decays of X can be further studied: \( X(3940) \rightarrow D\bar{D}^*, X(4160) \rightarrow D^*\bar{D}^* \) found in \( J/\psi D^* \) recoil

Decays of X can be further studied:
- \( X(3940) \rightarrow D\bar{D}^* \)
- \( X(4160) \rightarrow D^*\bar{D}^* \)

A lot more to do at Belle II:
- Full list of the states accessible, with better accuracy eg. \( \chi_{c0}(2P) \)
- Angular analyses giving access to the ratio of different \( L \) contributions
- \( e^+e^- \rightarrow \eta_c X / \chi_c X \) ... to be explored for the \( C \)-odd states!
Summary

- Heavy quarkonium spectroscopy is an active field, and many unsolved puzzles on the nature of dozens of exotic states
- SuperKEK and Belle II experiment are on the track for physics data taking in 2018
  - Expecting a x40 higher luminosity and a x50 larger data sample
- Plenty of studies on spectroscopy using Belle II data
  - Bottomonia studies at high energy eg. Y(5S), Y(6S) starting soon in early data-taking
  - 200~300 fb$^{-1}$ Y(3S) data-taking motivated
  - Charmonium(-like) states will be studied comprehensively in B decays, ISR and double production
Backup
Observation of $Z_b$ in $\Upsilon(5S)$ at Belle

- Charged $Z_b^+$ state is observed in $\Upsilon(5S)$
  - $\Upsilon(5S) \rightarrow Z_b^+ \pi^- \rightarrow \Upsilon(nS)\pi^+\pi^- / h_b(mP)\pi^+\pi^-$, $n=1,2,3$, $m=1,2$
- $Z_b(10610)$ and $Z_b(10650)$ also found in $B\bar{B}^*$ and $B^*\bar{B}^*$ final states

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PRL 108, 122001 (2012)

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PRL 116, 212001 (2016)
200~300 fb$^{-1}$ at or around Y(3S) will enable many studies like:

- Rare $\eta$ transitions
- Spectroscopy of D and F waves
- Hindered (M1) radiative transitions
- Antitritium and He-3 in Y decays