Exotic and conventional Quarkonium(-like) Physics Prospects at Belle II

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“X Y Z” — the beginning

\[ X(3872) \]
\[ PRL 91, 262001 (2003) \]
\[ B^\pm \rightarrow K^\pm[\pi^+\pi^- J/\psi] \]

\[ Y(4260) \]
\[ PRL 95, 142001 (2005) \]
\[ e^+e^- \rightarrow \gamma[\pi^+\pi^- J/\psi] \]

\[ Z_c(4430)^\pm \]
\[ PRL 100, 142001 (2008) \]
\[ B \rightarrow K[\pi^\pm J/\psi'] \]
If I could remember the names of all these particles, I'd be a botanist.
- E. Fermi
Various interpretations of the exotic states

- Hadroquarkonium
- Diquark-diantiquark
- Tetra-quark
- Q̅q̅-gluon “hybrid”
- D-̅D* “molecule”

Notable question on the exotic states
- What are the nature of these states? Quantum numbers?
- Why are they surprisingly narrow, even though they are above threshold?
- History of the quarkonium-like exotic states
- Belle accounts for ~1/2 of the discoveries, including the very first one, X(3872)

adapted from Lebed, Mitchell, Swanson, *PPNP* 93, 143 (2017)
Overview

Introduction

Action items for Belle II

- Charmonium-like exotics
- Bottomonium-like exotics

Closing remarks
SuperKEKB

Belle II

**Diagram**
- Electron ring
- Positron ring
- Positron damping ring
- Interaction Region
- Belle II detector
- Injector to Linac

**Equations**
\[ e^- \rightarrow (\ast) \rightarrow e^+ \]
\[ \mathcal{L}_{\text{peak}} = 40 \times \mathcal{L}_{\text{peak, Belle}} \]
\[ \int_{\text{goal}} \mathcal{L} \, dt = 50 \text{ ab}^{-1} = 50 \times \mathcal{L}_{\text{int, Belle}} \]
Quarkonium production in $e^+e^-$

- B decays
  - $(c\bar{c})$ only
  - all quantum numbers
- Initial-state radiation (ISR)
  - $J^{PC} = 1^{--}$
- two-photon process
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$
- double charmonium
  - e.g. $e^+e^- \rightarrow J/\psi X (3940)$
- quarkonium transitions

Belle, PRL 98, 082001 (2007)
Charmonium-like exotics
**X(3872) — action items for Belle II**

**Nature of X(3872)?**

- Search for a charged partner of X(3872)
- can give crucial input, if found, for the nature of X(3872)
- existing search (and null results) by BaBar
- isovector hypothesis of X(3872) is excluded; null hypothesis over isovector by a factor $1.1 \times 10^4$

$$X^- \rightarrow J/\psi \pi^- \pi^0$$
**X(3872) — action items for Belle II**

1. **Nature of X(3872)?**
2. **Connection with Y(4260)?**
   - Y(4260) → Z_c(3900)± π is observed
   - Y(4260) → γ X(3872) studied by BESIII
   - Detailed study of these by Belle II is necessary
   - ×4 effective luminosity from Belle II with 50 ab⁻¹
X(3872) — action items for Belle II

- Nature of X(3872)?
- Connection with Y(4260)?
- Absolute branching fractions?
  - Absolute measurement of $\text{BF}(B^+ \rightarrow X(3872) K^+)$ is useful to obtain $\text{BF}$ of $X(3872)$ to a specific final state, hence understand its properties.
  - This can be done in $e^+e^-$ $B$-factory, by $M_{\text{miss}}$.
  - Proof of principle by $\text{BF}(B^+ \rightarrow D^{(*)} \pi^+)$.
**PRD 97, 012005 (2018)**

\[ B^+ \rightarrow X_{c\bar{c}}K^+ \text{ by } M_{\text{miss}} \]

\[ \mathcal{B}(B^+ \rightarrow \eta_c(2S)K^+) = (4.8 \pm 1.1 \pm 0.3) \times 10^{-4} \quad \mathcal{B}(B^+ \rightarrow X(3872)K^+) < 2.6 \times 10^{-4} \]
X(3872) — action items for Belle II

- Nature of X(3872)?
- Connection with Y(4260)?
- Absolute branching fractions?

For other exotics

- Lineshape, e.g. for Y(4260)
- Determine $J^{PC}$ (not determined for many exotic states)
- dependence on production mechanism?
Production mechanism?

- **Belle two-photon**
  - observed X(4350) in $\gamma\gamma \rightarrow J/\psi \phi$

- **LHCb amplitude analysis of $B \rightarrow J/\psi \phi K$**
  - several resonant structures: Y(4140), Y(4274), X(4500), X(4700)
  - but did not see X(4350)

- **Belle II should revisit this mode in all ways possible ($B$, ISR, 2$\gamma$)**
Bottomonium-like exotics
**exotic states:** $Z_b(10610)$, $Z_b(10650)$

Note: $\Upsilon(5S)$ is an $h_b$-factory!
Bottomonia from $e^+e^-$ $B$-factories

Important past contributions
- discovery of $h_b$, $\eta_b$
- anomalous $\pi\pi$ and $\eta$ transitions
- discovery of $Z_b$: exotic (charged), around $B^{(*)}\bar{B}^*$ threshold

Operation energies

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\Upsilon(4S)$</th>
<th>$\Upsilon(5S)$</th>
<th>$\Upsilon(6S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>1.2 (21)</td>
<td>1.2 (10)</td>
<td>1.2 (5)</td>
<td>16 (17.1)</td>
<td>0.1 (0.4)</td>
<td>-</td>
</tr>
<tr>
<td>BaBar</td>
<td>-</td>
<td>14 (99)</td>
<td>30 (122)</td>
<td>433 (471)</td>
<td>$R_b$ scan</td>
<td>$R_b$ scan</td>
</tr>
<tr>
<td>Belle</td>
<td>6 (102)</td>
<td>25 (158)</td>
<td>3 (12)</td>
<td>711 (772)</td>
<td>121 (36)</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- With $\sim 1.5$ ab$^{-1}$ @ $\Upsilon(4S)$ existing, it might be sensible to run for non-B physics in early Belle II operations
action items for $b\bar{b}$-like @ Belle II

Energy scan — motivations

- $\Upsilon(10860)$ has been interpreted to be a pure $S$-wave, $J^{PC} = 1^{--}$
- But $\exists$ several questions to this: peak shifts, anomalously high rates to $\Upsilon(nS)\pi\pi$, non-suppression of spin-flip processes, etc.
- Moreover, all cross sections around $\Upsilon(10860)$ and $\Upsilon(11020)$ show similar structure
  - Just two peaks — “5$S$” and “6$S$”
  - This difference, to charmonia, is not understood
- The exclusive scan results (top 3) are certainly limited by statistics
action items for $b\bar{b}$-like @ Belle II

Energy scan — recent Belle results

- $h_b(1P)\pi\pi$
- $h_b(2P)\pi\pi$

**single $Z_b(10610)$ hypothesis is excluded at 3.3σ**

**single $Z_b(10650)$ hypothesis is not excluded**

For more on Belle energy scan results (esp. 1806.06203), see L. Piilonen talk.

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**PRL 117, 142001 (2016)**

**FIG. 4.** The $e^+e^-$ events mass distributions for the two decay modes $b\bar{b}\to\pi^+\pi^−X$ and $b\bar{b}\to\pi^+\pi^−\pi^0X$. The solid histograms represent the fits with the cross sections in Table VIII. The data are represented by the solid circle symbols. The thin dashed-dotted lines are the phase-space predictions with no continuum contribution. The thick dashed-dotted line is the result with the corresponding systematic uncertainty included at the 3σ level.
action items for $b\bar{b}$-like @ Belle II

- **Energy scan**
  - Understand $\Upsilon(6S) \to Z_b$ processes
    - $\Upsilon(6S) \to \pi^+\pi^- h_b(mP), \pi^+\pi^- \Upsilon(nS)$
    - transitions with $\pi^0\pi^0$?

- **Run at 6S**
  - Search for $W_b$, molecular partner of $Z_b$
    - $\Upsilon(5S, 6S) \to \gamma W_{b0}, \Upsilon(6S) \to \pi^+\pi^- W_{b0}$,
      where $W_{b0} \to \eta_b\pi, \chi_b\pi, \Upsilon\rho$

$^{13}$RADIATIVE TRANSITIONS FROM $H/C_6^{0}$ TO $C_7^{0}$

$H/C_10^{0}$:

- $\pi^+\eta_b\pi, \chi_b\pi, \Upsilon\rho$
- $\gamma, \gamma$
- $\Upsilon(5S), \Upsilon(6S)$

$B^*\bar{B}$:

- $\Upsilon(5S), \Upsilon(6S)$
- $\chi_b\pi, \gamma$

$B\bar{B}$:

- $\Upsilon(5S), \Upsilon(6S)$
- $\chi_b\pi, \gamma$

$IC(J^P)$: $1^+(1^+)$, $1^-(0^+)$, $1^-(1^+)$, $1^-(2^+)$

from Voloshin, *PRD* 93, 143 (2017)
action items for $b\bar{b}$-like @ Belle II

- Energy scan
- Run at 6S

“Energy frontier” ( > 11.24 GeV)

- Previously unexplored
- To study potentially interesting baryon-antibaryon dynamics
  \[ \Lambda_b \bar{\Lambda}_b \] threshold at \( \sim 11.24 \text{ GeV} \)
- Transitions from new vector states possibly provide a way of producing partners of X(3872), Z_b(106*0), etc.

Necessary to go beyond \( \sim 11.5 \text{ GeV} \) to access such transitions kinematically

But, it requires a Linac upgrade, which costs a lot.
action items for $b\bar{b}$-like @ Belle II

- Energy scan
- Run at 6S
- “Energy frontier” ( > 11.24 GeV)
- Full amplitude analyses to determine $J^P$ of exotics
There is no consensus about the interpretation for the observed exotic states, and different assumed structures lead to different predictions.

A lot of work is waiting for Belle II, to complete our experimental knowledge of the exotic states.

Belle II shall search for missing quarkonia and for expected partners of exotic states, search for new decay channels of known states, and detailed measurement of all accessible properties, including $J^P$, absolute BF, line-shapes, etc.
Back-up
### $b\bar{b}$-like molecular states

<table>
<thead>
<tr>
<th>$I^G(J^P)$</th>
<th>Name</th>
<th>Content</th>
<th>Co-produced particles</th>
<th>Decay channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>[Threshold, GeV/c$^2$]</td>
<td></td>
</tr>
<tr>
<td>1$^+$ (1$^+$)</td>
<td>$Z_b$</td>
<td>$B\bar{B}^*$</td>
<td>$\pi$ [10.75]</td>
<td>$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$</td>
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<tr>
<td>1$^+$ (1$^+$)</td>
<td>$Z'_b$</td>
<td>$B^<em>\bar{B}^</em>$</td>
<td>$\pi$ [10.79]</td>
<td>$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$</td>
</tr>
<tr>
<td>1$^-$ (0$^+$)</td>
<td>$W_{b0}$</td>
<td>$B\bar{B}$</td>
<td>$\rho$ [11.34], $\gamma$ [10.56]</td>
<td>$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$</td>
</tr>
<tr>
<td>1$^-$ (0$^+$)</td>
<td>$W'_{b0}$</td>
<td>$B^<em>\bar{B}^</em>$</td>
<td>$\rho$ [11.43], $\gamma$ [10.65]</td>
<td>$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$</td>
</tr>
<tr>
<td>1$^-$ (1$^+$)</td>
<td>$W_{b1}$</td>
<td>$B\bar{B}^*$</td>
<td>$\rho$ [11.38], $\gamma$ [10.61]</td>
<td>$\Upsilon(nS)\rho$</td>
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<tr>
<td>1$^-$ (2$^+$)</td>
<td>$W_{b2}$</td>
<td>$B^<em>\bar{B}^</em>$</td>
<td>$\rho$ [11.43], $\gamma$ [10.65]</td>
<td>$\Upsilon(nS)\rho$</td>
</tr>
<tr>
<td>0$^-$ (1$^+$)</td>
<td>$X_{b1}$</td>
<td>$B\bar{B}^*$</td>
<td>$\eta$ [11.15]</td>
<td>$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$</td>
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<tr>
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<td>$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$</td>
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<td>$B\bar{B}$</td>
<td>$\omega$ [11.34], $\gamma$ [10.56]</td>
<td>$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$</td>
</tr>
<tr>
<td>0$^+$ (0$^+$)</td>
<td>$X'_{b0}$</td>
<td>$B^<em>\bar{B}^</em>$</td>
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<td>$B^<em>\bar{B}^</em>$</td>
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