Quarkonium states at $B$-factories

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Quarkonium & $B$-factories

The study of quarkonium spectroscopy has been re-vitalized in recent years thanks to a series of new measurements performed by $B$-factories on their large data samples, mainly at $\Upsilon(4S)$ peak:

- CLEO III (1989 - 2001): $\mathcal{L} \approx 9 \text{ fb}^{-1}$
- $\text{BABAR}$ (1999 - 2008): $\mathcal{L} \approx 430 \text{ fb}^{-1}$
- Belle (1999 - ): $\mathcal{L} \approx 800 \text{ fb}^{-1}$

New results also from charm factories (BES, CLEO-c), Tevatron (CDF, D0), $p\bar{p}$ formation (E835)
Outline

Charmonium at $B$-factories:

- the first surprise: $X(3872)$;
- new resonances at $3940$ MeV/$c^2$;
- vector states: the ‘$Y$’ series;
- and yet more...

Bottomonium at $B$-factories:

- new decays of the $Y(4S)$;
- anomalous decays of the $Y(5S)$
Charmonium production at $B$-factories

At $B$-factories, charmonium is copiously produced through a variety of processes:

- **production in $B$ decays:**
  \[ B(B \to (c\bar{c})\,X) \sim 3\% \]
  \[ \implies \sim 3\text{M decays in }100\text{ fb}^{-1}; \]

- **production in continuum $e^+ e^-$ annihilation:**
  \[ \sigma(e^+ e^- \to J/\psi\,X) \sim 2.5\text{ pb} \implies \sim 250k J/\psi \text{ in }100\text{ fb}^{-1}; \]

- **two-photon fusion**
  \[ (e^+ e^- \to e^+ e^-\,\gamma\,\gamma \to e^+ e^-\,(c\bar{c})\,): \]
  \[ \sim 1\text{M }\eta_c \text{ in }100\text{ fb}^{-1}; \]

- **production via initial state radiation:**
  \[ \sigma(e^+ e^- \to J/\psi\,\gamma) \sim 2\text{ pb} \implies \sim 350k J/\psi \text{ in }100\text{ fb}^{-1} \]
The charmonium spectrum

All states below open-charm thresholds have been observed by Belle, confirmed by BABAR and CLEO in 3 different production channels recently observed by CLEO-c in $\psi(2S)$ decays.

spectroscopic notation

observed by Belle, confirmed by BABAR and CLEO in 3 different production channels

2 $m(D^0)$

recently observed by CLEO-c in $\psi(2S)$ decays

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The $X(3872)$ state

Discovered by Belle (2003) in $B^\pm \rightarrow X(3872) \, K^\pm$, $X \rightarrow J/\psi \, \pi^+ \, \pi^-$
Confirmed by CDF, D0, CLEO, B\textit{A}B\textit{A}R

Production modes:

- $B$ decays: $B \rightarrow X(3872) \, K$;
- prompt $p\bar{p}$;
- not seen in prompt $e^+e^-, \gamma \gamma$

Decay modes:

- $X \rightarrow J/\psi \, \pi^+ \, \pi^-$ (consistent with $X \rightarrow J/\psi \, \rho$);
- $X \rightarrow J/\psi \, \gamma$;
- $X \rightarrow D \, \bar{D}^*$

CDF angular analysis + decay modes
$\Rightarrow J^{PC}(X(3872)) = 1^{++}$ favoured
**X(3872): theoretical interpretations**

**Charmonium state:**
- disfavoured: mass and BRs disagree with predictions

**$D^0 - D^{*0}$ molecule:**
- $J^{PC} = 1^{++}$ favoured, mass consistent with expected;
- accommodates competing decay modes

**Tetraquark:**
- small width expected;
- would imply 2 neutral + 2 charged states

**Hybrid:**
- predicted mass $> 4200$ MeV
\( X(3872) \rightarrow J/\psi \, \pi^+ \, \pi^- \)

\( B^\pm \rightarrow (J/\psi \, \pi^+ \, \pi^-) \, K^\pm \)

\( B^0 \rightarrow (J/\psi \, \pi^+ \, \pi^-) \, K_s \)

\[ M = (3872.0 \pm 0.6 \pm 0.5) \, \text{MeV}/c^2 \]
\[ \Delta M = (0.22 \pm 0.90 \pm 0.27) \, \text{MeV}/c^2 \]
\[ R(B^0/B^+) = 0.94 \pm 0.24 \pm 0.10 \]

\[ M = (3871.3 \pm 0.6 \pm 0.1) \, \text{MeV}/c^2 \]
\[ \Delta M = (2.7 \pm 1.6 \pm 0.4) \, \text{MeV}/c^2 \]
\[ R(B^0/B^+) = 0.41 \pm 0.25 \pm 0.05 \]

No significant evidence of mass splitting expected in the tetraquark model

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$X(3872) \to D \bar{D}^*$

\[
\mathcal{L} = 605 \text{ fb}^{-1}
\]

\[
M = (3875.4 \pm 0.7^{+0.7}_{-1.7} \pm 0.8) \text{ MeV}/c^2
\]

\[
\mathcal{B} = (1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}
\]

\[
\text{Cmp. } \mathcal{B}(B^+ \to X K^+, J/\psi \pi^+ \pi^-) = (1.14 \pm 0.20) \times 10^{-5} \quad (\text{PDG '06})
\]

Significant mass difference with what measured in $X \to J/\psi \pi^+ \pi^-$

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Two $X$?

The mass values measured in the two decay modes $X \rightarrow J/\psi \pi^+ \pi^-$, $X \rightarrow D \bar{D} \pi$ show a poor consistency $\Rightarrow$ two different states? (as predicted by the tetraquark model)

A simple model explains the observed mass shift as a consequence of the proximity of the $D^0D^{0*}$ threshold

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HQL '08 - Melbourne, June 5, 2008
Three states at 3940 MeV/c^2

<table>
<thead>
<tr>
<th>Production/decay mode</th>
<th>J^PC</th>
<th>Mass (MeV)</th>
<th>Γ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X e^+e^- → J/ψ X, X → D\bar{D}^*</td>
<td>0^-, 1^{++}</td>
<td>3943 ± 6 ± 6</td>
<td>&lt; 52</td>
</tr>
<tr>
<td>Y B → Y K, Y → J/ψ ω</td>
<td>1^{++},...</td>
<td>3943 ± 11 ± 13</td>
<td>87 ± 22 ± 26</td>
</tr>
<tr>
<td>Z γ γ → Z, Z → D\bar{D}</td>
<td>2^{++}</td>
<td>3929 ± 5 ± 2</td>
<td>29 ± 10 ± 2</td>
</tr>
</tbody>
</table>

Phys. Rev. Lett. 98, 082001

Phys. Rev. Lett. 94, 182002

Phys. Rev. Lett. 96, 082003

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HQL ’08 - Melbourne, June 5, 2008
Y(3940) \rightarrow J/\psi \omega \text{ at BABAR}

Correlation between $B$ signal (using $m_{ES}$) and $\omega$ signal verified using projections in the angular distributions \(\Rightarrow\) close to 100%

Results extracted fitting number of signal events in slices of $m(J/\psi \omega)$

\[
M = (3914.6^{+3.8}_{-3.4} \pm 1.9) \text{ MeV}/c^2
\]

\[
\Gamma = (34^{+12}_{-8} \pm 5) \text{ MeV}/c^2
\]

Mass lower, width narrower than Belle \(\Rightarrow\) same state as $X(3940)$?

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The ‘Y’ vector states

Two $J^{PC} = 1^{−}$ states observed by BABAR in ISR production:

**Y(4260) → $J/\psi \pi^+ \pi^−$**

**Y(4350) → $\psi(2S) \pi^+ \pi^−$**

**Y(4260) confirmed by CLEO and CLEO-c (also Y(4260) → $J/\psi \pi^0 \pi^0$)**

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More Ys from Belle

From a similar analysis on ISR events, Belle found confirmation for the two states, and found evidence for two more vector states.

Phys. Rev. Lett. 99, 182004

Phys. Rev. Lett. 99, 142002

\[ \mathcal{L} = 548 \text{ fb}^{-1} \]

\[ \mathcal{L} = 673 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>( \mathbf{M} ) (MeV)</th>
<th>( \mathbf{\Gamma} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4008 ± 40 ( ^{+114}_{-28} )</td>
<td>4247 ± 12 ( ^{+17}_{-32} )</td>
</tr>
<tr>
<td>226 ± 44 ± 87</td>
<td>108 ± 19 ± 10</td>
</tr>
<tr>
<td>4361 ± 9 ± 9</td>
<td>4664 ± 11 ± 5</td>
</tr>
<tr>
<td>74 ± 15 ± 10</td>
<td>48 ± 15 ± 3</td>
</tr>
</tbody>
</table>
### New states: summary

<table>
<thead>
<tr>
<th>State</th>
<th>Experiment</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Production</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>Belle, CDF, D0, Cleo, BaBar</td>
<td>3871.2 ± 0.5</td>
<td>&lt; 2.3</td>
<td>$1^{++}, 2^{-}$</td>
<td>B decays, $p\bar{p}$</td>
<td>$J/\psi \pi^+ \pi^-, J/\psi \gamma$</td>
</tr>
<tr>
<td>X(3875)</td>
<td>Belle, BaBar</td>
<td>3875.2 ± 0.7</td>
<td></td>
<td></td>
<td>B decays</td>
<td>$D^0 D^0 \pi^0, D^0 \bar{D}^0$</td>
</tr>
<tr>
<td>X(3940)</td>
<td>Belle</td>
<td>3943 ± 6 ± 6</td>
<td>&lt; 52</td>
<td>$J^{++}$</td>
<td>B decays</td>
<td></td>
</tr>
<tr>
<td>Y(3940)</td>
<td>Belle, BaBar</td>
<td>3914.6 $^{+3.8}_{-3.4}$ ± 1.9</td>
<td>34 $^{+12}_{-8}$ ± 5</td>
<td>$J^{++}$</td>
<td>B decays</td>
<td></td>
</tr>
<tr>
<td>Z(3930)</td>
<td>Belle</td>
<td>3929 ± 5 ± 2</td>
<td>29 ± 10 ± 2</td>
<td>$2^{++}$</td>
<td>$\gamma \gamma$</td>
<td>$D^0 \bar{D}^0, D^+ D^-$</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>Belle</td>
<td>4008 ± 40 $^{+114}_{-28}$</td>
<td>226 ± 44 ± 87</td>
<td>$1^{--}$</td>
<td>e$^+$ e$^-$</td>
<td>$J/\psi \pi^+ \pi^-, J/\psi \pi^0 \pi^0$</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>BaBar, Cleo, Belle</td>
<td>4247 ± 12 $^{+17}_{-32}$</td>
<td>108 ± 19 ± 10</td>
<td>$1^{--}$</td>
<td>e$^+$ e$^-$</td>
<td></td>
</tr>
<tr>
<td>Y(4350)</td>
<td>BaBar, Belle</td>
<td>4361 ± 9 ± 9</td>
<td>74 ± 15 ± 10</td>
<td>$1^{--}$</td>
<td>e$^+$ e$^-$</td>
<td>$\psi(2S) \pi^+ \pi^-$</td>
</tr>
<tr>
<td>Y(4660)</td>
<td>Belle</td>
<td>4664 ± 11 ± 5</td>
<td>48 ± 15 ± 3</td>
<td>$1^{--}$</td>
<td>e$^+$ e$^-$</td>
<td>$\psi(2S) \pi^+ \pi^-$</td>
</tr>
<tr>
<td>Y(4160)</td>
<td>Belle</td>
<td>4156 $^{+25}_{-20}$ ± 15</td>
<td>139 $^{+111}_{-61}$ ± 21</td>
<td>$J^{++}$</td>
<td>e$^+$ e$^-$ (J/ψ recoil)</td>
<td>$D^* D^*$</td>
</tr>
<tr>
<td>Z$^+$ (4430)</td>
<td>Belle</td>
<td>4433 ± 4 ± 2</td>
<td>44 $^{+18}<em>{-13}$ $^{+30}</em>{-13}$</td>
<td></td>
<td>B decays</td>
<td></td>
</tr>
</tbody>
</table>

**Many new states, few new charmonia?**

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Bottomonium at $B$-factories

It is usually assumed that $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \approx 100\% \Rightarrow B$-factories:

- however, the size of the data samples allows to search for rarer, non-$B\bar{B}$ decays;
- moreover, states below the open-$B$ threshold can be reached via the ISR mechanism, providing some of the largest data sets recorded

Special data sets taken by Belle and BABAR at different energies:

- Belle: $\Upsilon(3S)$ peak, 3 fb$^{-1}$; $\Upsilon(5S)$ scan, 2 fb$^{-1}$; $\Upsilon(5S)$ peak 21.7 fb$^{-1}$ ($\approx 40 \times$ pre-existing sample)
- BABAR: $\Upsilon(2S)$ peak, 15 fb$^{-1}$; $\Upsilon(3S)$ peak, 30 fb$^{-1}$; R-scan $\Upsilon(4S) \to 11.3$ MeV/c$^2$, 3 fb$^{-1}$ (all $\approx 10 \times$ pre-existing sample)

$\Rightarrow$ quest for missing states and search for bottomonium-like equivalent of charmonium-like new states
The bottomonium spectrum

Several states below open-bottom threshold still missing: in particular, pseudo-scalar ($\eta_b$) states

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Y(4S) hadronic decays

First non-\(B\bar{B}\) hadronic decays of Y(4S) observed by BABAR on 211 fb\(^{-1}\) of data: \(Y(4S) \to Y(1S, 2S) \pi^+ \pi^-\). Confirmed by Belle

Update on 347 fb\(^{-1}\): new, improved measurements of:

- \(\mathcal{B}(Y(4S) \to Y(1S, 2S) \pi^+ \pi^-)\);
- \(\mathcal{B}(Y(3S) \to Y(2S) \pi^+ \pi^-)\);
- \(\mathcal{B}(Y(3S, 2S) \to Y(1S) \pi^+ \pi^-)\);
- \(\Gamma(Y(mS) \to Y(1S) \pi^+ \pi^-)/\Gamma(Y(mS) \to Y(2S) \pi^+ \pi^-)\)

First observation of \(Y(4S) \to Y(1S) \eta\):

- anomalously large

\[
\frac{\Gamma(Y(4S) \to Y(1S) \eta)/\Gamma(Y(4S) \to Y(1S) \pi^+ \pi^-)}{= 2.41 \pm 0.40 \pm 0.12}
\]
gaining insight in (as yet poorly known) Y hadronic decays

<table>
<thead>
<tr>
<th>Transition</th>
<th>$N_{\text{cand}}$</th>
<th>$N_{\text{bck}}$</th>
<th>$N_{\text{corr}}$</th>
<th>Signif.</th>
<th>Our Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ (meV)</td>
<td>9036</td>
<td>156±11</td>
<td>24319±268</td>
<td>2582±28±94</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to e^+e^-)$ (meV)</td>
<td>3139</td>
<td>230±9</td>
<td>25202±574</td>
<td>2618±60±97</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$ (meV)</td>
<td>0</td>
<td>2.5±1.1</td>
<td>&lt;28</td>
<td>&lt;3.1</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ (meV)</td>
<td>4198</td>
<td>207±10</td>
<td>9945±174</td>
<td>457±8±18</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to e^+e^-)$ (meV)</td>
<td>3604</td>
<td>1234±20</td>
<td>9821±261</td>
<td>441±12±18</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(2S) \to e^+e^-)$ (meV)</td>
<td>975</td>
<td>180±21</td>
<td>4477±241</td>
<td>206±11±12</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$ (meV)</td>
<td>1</td>
<td>0.8±0.4</td>
<td>&lt;41</td>
<td>&lt;2.0</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S) \to \eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to e^+e^-)\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$ (meV)</td>
<td>4</td>
<td>2.8±0.8</td>
<td>&lt;210</td>
<td>&lt;9.6</td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$ ($\times 10^6$)</td>
<td>687</td>
<td>378±11</td>
<td>739±60</td>
<td>1.99±0.16±0.07</td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to e^+e^-)$ ($\times 10^6$)</td>
<td>1057</td>
<td>934±17</td>
<td>676±397</td>
<td>1.76±1.05±0.06</td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))\mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-)$ ($\times 10^6$)</td>
<td>377</td>
<td>204±8</td>
<td>615±78</td>
<td>1.65±0.21±0.11</td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S))\mathcal{B}(\Upsilon(2S) \to e^+e^-)$ ($\times 10^6$)</td>
<td>251</td>
<td>206±8</td>
<td>669±392</td>
<td>1.76±1.03±0.11</td>
<td></td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$ ($\times 10^6$)</td>
<td>40</td>
<td>0.2±0.4</td>
<td>387±60</td>
<td>11σ</td>
<td>1.08±0.17±0.05</td>
</tr>
<tr>
<td>$B(\Upsilon(4S) \to \eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S) \to e^+e^-)\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$ ($\times 10^6$)</td>
<td>16</td>
<td>0.7±0.6</td>
<td>424±106</td>
<td>6.2σ</td>
<td>1.15±0.29±0.05</td>
</tr>
</tbody>
</table>
Anomalous $Y(5S)$ decay rates at Belle

Similar analysis on Belle sample at $Y(5S)$ c.m. energy:

- look for $l^+ l^- \pi^+ \pi^-$ final state and plot $m(l^+ l^-)$ vs. $m(l^+ l^- \pi^+ \pi^-) - m(l^+ l^-)$

Assuming published values for $Y(5S)$ parameters, rates are $\sim 100 \times$ similar rates for bottomonium:

- equivalent states of charmonium $Y$?
Conclusions

In recent years, $B$-factories have been playing a starring role in the study of charmonium and bottomonium systems. A partially unexpected wealth of results in this field:

- significant contribution to the knowledge of quarkonium spectroscopy and production/decay mechanisms;
- discovery of many quarkonium-like states of uncertain interpretation, possibly disclosing a door on a new spectroscopy of non-conventional structures (exotics)

Despite (some) data taking coming to an end, important results can still come from several analyses on the complete data sets

- in particular, recent ‘ad-hoc’ data sets taken in the bottomonium region
Back-up
**BABAR data sample**

**BABAR Run 7**

- **PEP II Delivered Luminosity**: 553.48/fb
- **BaBar Recorded Luminosity**: 531.43/fb
- **BaBar Recorded Y(4s)**: 432.89/fb
- **BaBar Recorded Y(3s)**: 30.23/fb
- **BaBar Recorded Y(2s)**: 14.45/fb
- **Off Peak Luminosity**: 53.85/fb

Graphs showing integrated luminosity from 2000 to 2008.
Belle data sample

Offline+Online Luminosity (pb⁻¹) (/day)

Integrated Luminosity (pb⁻¹)

Belle log total: 832463 pb⁻¹

Date: 4/16/1999 to 11/14/2008