Bottomonium

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Workshop on New Hadrons, Busan Nov. 2012
Yb or Y(5S)?
The triple cascade to parabottomonia
D waves
Hadronic Transitions
### Integrated Luminosities (in fb\(^{-1}\))

<table>
<thead>
<tr>
<th>Luminosity (fb(^{-1}))</th>
<th>States</th>
<th>Total (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>Y(5S)</td>
<td></td>
</tr>
<tr>
<td>711</td>
<td>Y(4S)</td>
<td>433</td>
</tr>
<tr>
<td>3.0</td>
<td>Y(3S)</td>
<td>30</td>
</tr>
<tr>
<td>24</td>
<td>Y(2S)</td>
<td>14</td>
</tr>
<tr>
<td>5.7</td>
<td>Y(1S)</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>Off resonance</td>
<td>54</td>
</tr>
<tr>
<td>68</td>
<td>scans</td>
<td></td>
</tr>
<tr>
<td>1020</td>
<td>total</td>
<td>531</td>
</tr>
</tbody>
</table>
A large excess of $Y(1,2S)\pi\pi$ at 5S peak triggered a high luminosity study (6 points, 1fb$^{-1}$ each) of the region 10.8-11.1. $Y(1,2S)\pi\pi$ yields peak 20 MeV above 5S. Is this a bottom partner of $Y(4260)$?

<table>
<thead>
<tr>
<th>Process</th>
<th>Peak $\sigma$ (pb)</th>
<th>$\mu$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(1S)\pi\pi$</td>
<td>$2.46^{+0.27}_{-0.25} \pm 0.18$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y(2S)\pi\pi$</td>
<td>$4.18^{+0.49}_{-0.46} \pm 0.55$</td>
<td>$10889.6 \pm 1.8 \pm 1.5$</td>
<td>$54.7^{+8.5}_{-7.2} \pm 2.5$</td>
</tr>
<tr>
<td>$Y(3S)\pi\pi$</td>
<td>$1.61^{+0.31}_{-0.28} \pm 0.21$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<tr>
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<th>$\mu$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(1S)\pi\pi$</td>
<td>$2.03^{+0.27}_{-0.22} \pm 0.15$</td>
<td>$10887.4^{+4.1}_{-4.5} \pm 1.6$</td>
<td>$74^{+19}_{-14} \pm 3$</td>
</tr>
<tr>
<td>$Y(2S)\pi\pi$</td>
<td>$5.77^{+0.90}_{-0.80} \pm 0.67$</td>
<td>$10890.3^{+2.3}_{-1.9} \pm 1.4$</td>
<td>$37.0^{+7.9}_{-6.2} \pm 3.1$</td>
</tr>
<tr>
<td>$Y(3S)\pi\pi$</td>
<td>$1.65^{+0.36}_{-0.32} \pm 0.21$</td>
<td>$10882.3^{+7.2}_{-7.3} \pm 1.5$</td>
<td>$52^{+20}_{-14} \pm 1$</td>
</tr>
</tbody>
</table>
Scan of the Y(5S)-Y(6S) region: Babar


Ldt 25 pb\(^{-1}\) per point, 
E=10.54-11.2 ; dE=5 MeV 
Total 3.3 fb\(^{-1}\)

\[ R_b = \frac{\sigma(bb)}{\sigma(\mu\mu)} \]

Tetraquark Candidate at 10.91?

**Predicted by Tornqvist in 1984!!**
Scan of the Y(5S)-Y(6S) region: Belle vs Babar

A. Bondar: ICHEP2012 (preliminary)
No evidence of Ali peaks
Exclusive Reconstruction of $\eta_c$ in 12 decay modes:

\[
\begin{align*}
\pi^+\pi^+\pi^-\pi^- & \quad K^+K^-\pi^+\pi^- \\
\pi^+\pi^+\pi^-\pi^0 & \quad K^+K^-\pi^+\pi^- \\
\pi^+\pi^+\pi^-\pi^- & \quad K^+K^-\pi^+\pi^- \\
K^+K^-\pi^0 & \quad K^+K^-\pi^+K^- \\
K^+K^-\pi^+K^- & \quad \eta\pi^+\pi^- \\
K^+K^-\pi^+K^- & \quad \eta\pi^+\pi^- \\
K^+K^-\pi^+K^- & \quad \eta\pi^+\pi^- \\
\end{align*}
\]

Cross section DOES NOT peak at 4170

CLEO: PRL 107 (2011) 041803

\begin{align*}
\text{(a)} & \quad e^+e^- \rightarrow \pi^+\pi^-\eta_c \rightarrow \gamma\pi^+\pi^-\eta_c \\
& \text{@4170 MeV} \\
\text{(b)} & \quad e^+e^- \rightarrow \eta\eta_c \rightarrow \gamma\eta\eta_c \\
& \text{@4170 MeV} \\
\text{(c)} & \quad e^+e^- \rightarrow \pi^+\pi^-\eta_c \rightarrow \gamma\pi^+\pi^-\eta_c \\
& \text{@4260 MeV} \\
\text{(d)} & \quad e^+e^- \rightarrow \psi' \rightarrow \pi^0\eta_c \\
& \rightarrow \gamma\pi^0\eta_c
\end{align*}
Simultaneous discovery of $h_b(1,2P)$!!

(*) In both cases the peak of dipion transition to narrow vectors is actually shifted with respect to $\Upsilon(5S)$ and $\psi(4170)$
\( h_b(1,2P) \) from \( \Upsilon(5S) \)

<table>
<thead>
<tr>
<th>( \Upsilon ) state</th>
<th>Yield, ( 10^3 )</th>
<th>Mass, MeV/c(^2 )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Upsilon(1S) )</td>
<td>105.2 ± 5.8 ± 3.0</td>
<td>9459.4 ± 0.5 ± 1.0</td>
<td>18.2 ( \sigma )</td>
</tr>
<tr>
<td>( h_b(1P) )</td>
<td>50.4 ± 7.8(^{+4.5}_{-9.1} )</td>
<td>9898.3 ± 1.1(^{+1.0}_{-1.1} )</td>
<td>6.2 ( \sigma )</td>
</tr>
<tr>
<td>( 3S \rightarrow 1S )</td>
<td>56 ± 19</td>
<td>9973.01</td>
<td>2.9 ( \sigma )</td>
</tr>
<tr>
<td>( \Upsilon(2S) )</td>
<td>143.5 ± 8.7 ± 6.8</td>
<td>10022.3 ± 0.4 ± 1.0</td>
<td>16.6 ( \sigma )</td>
</tr>
<tr>
<td>( \Upsilon(1D) )</td>
<td>22.0 ± 7.8</td>
<td>10166.2 ± 2.6</td>
<td>2.4 ( \sigma )</td>
</tr>
<tr>
<td>( h_b(2P) )</td>
<td>84.4 ± 6.8(^{+23.}_{-10} )</td>
<td>10259.8 ± 0.6(^{+1.4}_{-1.0} )</td>
<td>12.4 ( \sigma )</td>
</tr>
<tr>
<td>( 2S \rightarrow 1S )</td>
<td>151.7 ± 9.7(^{+9.0}_{-20} )</td>
<td>10304.6 ± 0.6 ± 1.0</td>
<td>15.7 ( \sigma )</td>
</tr>
<tr>
<td>( \Upsilon(3S) )</td>
<td>45.6 ± 5.2 ± 5.1</td>
<td>10356.7 ± 0.9 ± 1.1</td>
<td>8.5 ( \sigma )</td>
</tr>
</tbody>
</table>

Significance after correcting for systematics effects:
- \( h_b(1P) \) 5.5\( \sigma \)
- \( h_b(2P) \) 11.2\( \sigma \)

Masses very close to the state COG of \( \chi \) states, as expected from theory:
- \( \Delta M_{HF}(1P) = 1.6 \pm 1.5 \text{ MeV/c}^2 \)
- \( \Delta M_{HF}(2P) = 0.5^{+1.6}_{-1.2} \text{ MeV/c}^2 \)
Belle has discovered two charged bottomonium-like resonances:

\[ Z_b(10610) \quad M = 10608.1 \pm 1.7 \text{ MeV} \]
\[ \Gamma = 15.5 \pm 2.4 \text{ MeV} \]

\[ Z_b(10650) \quad M = 10653.3 \pm 1.5 \text{ MeV} \]
\[ \Gamma = 14.0 \pm 2.8 \text{ MeV} \]

The states are observed in 5 final states, all with consistent masses, close to the BB* and B*B* threshold.

Analysis of angular distributions suggests \( J^P=1^+ \) for these states.

PRL108,122001(2011)

Jin Li's talk:

The neutral partners \( Z_b^0 \)
Decays to BB* and B*B*
The high yield of $h_b(1,2P)$:

$$N[h_b(1P)] = (50.4 \pm 7.8 \pm 4.5) \times 10^3$$

$$N[h_b(2P)] = (84.4 \pm 6.8 \pm 23) \times 10^3$$

opens new perspectives to study the $\eta_b$.

Expected $E1$ rates:

*Godfrey & Rosner, PRD66 014012 (2002)*

$$h_b(1P) \rightarrow \gamma \eta_b(1S) = 41\%$$

$$h_b(2P) \rightarrow \gamma \eta_b(1S) = 13\%$$

$$h_b(2P) \rightarrow \gamma \eta_b(2S) = 19\%$$
Rediscovery of $\eta_b$

Babar 2008:

PRL 101,071801(2008)
PRL 103,161801(2009)
Rediscovery of $\eta_b$:

Babar 2008:

\[
\chi_b(2P) \rightarrow \gamma \eta(1S)\]

\[
\gamma_{\text{ISR}} Y(1S) \rightarrow \gamma \eta_b(1S)\]

\[
\chi_b(1P) \rightarrow \gamma Y(1S)\]

\[
\gamma_{\text{ISR}} Y(1S) \rightarrow \gamma \eta_b(1S)\]

\[
h_b(2P) \rightarrow \gamma \eta_b(1S)\]

\[
h_b(1P) \rightarrow \gamma \eta_b(1S)\]

ArXiv:1110.3934, 1205.6351

PRL 101,071801(2008)
PRL 103,161801(2009)
Is this $\eta_b(2S)$?

Significance: $4.2 \sigma$, including all systematics

$L dt = 121.4 \text{ fb}^{-1}(5S) + 12 \text{ fb}^{-1}$ (scan)

$h_b(2P) \rightarrow \gamma \eta_b(2S)$

Exclusive analysis of 26 final states (from CLEO data)

Charmonium: $\text{BR}(\psi' \rightarrow \gamma \eta_c(2S)) \sim 7 \times 10^{-4}$
$\text{BR}(\psi' \rightarrow \gamma \chi_{c0}(1P)) \sim 7 \times 10^{-2}$
$\Delta M_{\text{HF}}(2S)/\Delta M_{\text{HF}}(1S) = 48/112 = 0.43$

Bottomonium:
$\text{BR}(\Upsilon(2S) \rightarrow \gamma \eta_b(2S)) \sim \text{BR}(\Upsilon(2S) \rightarrow \gamma \chi_{b0}(1P))$ ??
$\Delta M_{\text{HF}}(2S)/\Delta M_{\text{HF}}(1S) = 50/60 = 0.83$ ??
Some tension with the most accurate NRQCD prediction, but very close to lattice QCD (Meinel) predictions.

Spin averaged 1P-1S splitting seems not to depend on scale!!

New Hadron Workshop, Busan, 19/
Parabottomonia
vs theory

$\eta_b(2S)$ vs $\eta_b(1S)$

- Spin averaged 1P-1S splitting seems not to depend on scale: only 1% relative difference with charmonium

- $\eta_b(2S)$ vs theory

- $\eta_b(1S)$ vs theory

- PNRQCD@NLL, PRL92,242001(2004)
- Lattice QCD, PRD82,114502(2010)
- Godfrey-Isgur, PRD32,189 (1985)

- 10 MeV discrepancy w/ earlier Babar and CLEO results

- $\Delta M_{HF}(\eta_b), \text{ MeV/}c^2$

- $\eta_b(1S)$

- $\eta_b(2S)$

- $\psi(3770)$

- $\chi_c(1P)$ and $h_c(1P)$

- M(1P) - $<M(1S)>$

- Charmonium $457.5\pm0.3 \text{ MeV/}c^2$
- Bottomonium $453.3\pm1.3 \text{ MeV/}c^2$

New Hadron Workshop, Busan, 19/
Eta Transitions

QCD multipole expansion:
\( Y' \rightarrow \eta Y : M_2*E_1+M_1*M_1 \)
\( Y' \rightarrow \pi\pi Y : E_1*E_1 \)
\( \frac{(Y' \rightarrow \eta Y)}{(Y' \rightarrow \pi\pi Y)} \sim \frac{1}{m_b^2} \)

B(Y(2S) \rightarrow \eta Y(1S))

theory: \( \sim 4 \times 10^{-4} \)

CLEO \textit{PRL101,192001} \( (2.10 \pm 0.70 \pm 0.40) \times 10^{-4} \)
BABAR \textit{PRD84 (1011) 92003} \( (2.39 \pm 0.31 \pm 0.14) \times 10^{-4} \)
Belle ArXiV:1210.6914 \( (3.57 \pm 0.25 \pm 0.21) \times 10^{-4} \)

Most recent Belle result has better agreement with theory
**Eta Transitions**

**BELLE:** from 5S:

\[
B(Y(5S) \rightarrow \eta Y(1S)) = (7.3 \pm 1.6 \pm 0.8) \times 10^{-4} = 0.25 \times B(Y(5S) \rightarrow \pi \pi Y(1S))
\]

\[
B(Y(5S) \rightarrow \eta Y(2S)) = (38 \pm 4 \pm 5) \times 10^{-4} = B(Y(5S) \rightarrow \pi \pi Y(2S))
\]

**Babar** *PRD78, 112002 (2008)*

\[
B(Y(4S) \rightarrow \eta Y(1S)) = (1.96 \pm 0.06 \pm 0.09) \times 10^{-4} (2.5 \times \pi \pi)!!!
\]

Voloshin: “QCDME not working with spatially broad objects, most likely to be described with Coupled Channel Effects”
2: η Transitions in Charmonium

\[ e^+ e^- \rightarrow \gamma_{\text{ISR}} \eta J/\psi \text{ at Belle} \]

\[
\begin{align*}
&\psi(4415) \quad \psi(4160) \\
&\eta(2S) \quad \chi_c(1P) \quad h_c(1P) \\
&\eta(1S) \\
\end{align*}
\]

Taking \( \Gamma_{e^+ e^-} (\psi(4040)) = (0.86 \pm 0.07) \text{ keV from PDG} \rightarrow \) 
\[
\begin{align*}
&B(\psi(4040) \rightarrow \eta J/\psi) = (0.59 \pm 0.11 \pm 0.14)\% \text{ or } \\
&B(\psi(4040) \rightarrow \eta J/\psi) = (1.44 \pm 0.18 \pm 0.18)\%. \\
\end{align*}
\]

Taking \( \Gamma_{e^+ e^-} (\psi(4160)) = (0.83 \pm 0.07) \text{ keV from PDG} \rightarrow \) 
\[
\begin{align*}
&B(\psi(4160) \rightarrow \eta J/\psi) = (0.50 \pm 0.07 \pm 0.11)\% \text{ or } \\
&B(\psi(4160) \rightarrow \eta J/\psi) = (1.83 \pm 0.21 \pm 0.24)\%. \\
\end{align*}
\]

\[ \text{Entries/20 MeV/c}^2 \]

\[
\begin{align*}
&M(\eta J/\psi) \text{ (GeV/c}^2) \\
&4 \quad 4.25 \quad 4.5 \quad 4.75 \\
\end{align*}
\]
Comparison of higher charmonium and bottomonium decays to narrow resonances will hopefully clarify the nature of the states above threshold. Further transitions in bottomonium are under study at Belle.
The two peaks at 10.26 and 10.28 are due to:
\( \chi_b(2P) \rightarrow \omega \Upsilon(1S) \) with \( \omega \rightarrow \pi\pi \) (1.5%)
D wave from 5S: Belle

Significance:
- Exclusive: $9\sigma$
- Inclusive: $2.4\sigma$

CLEO
$M = 10161.1 \pm 0.6 \pm 1.6$ MeV
$B[Y(3S) \rightarrow Y(1D)\gamma\gamma \rightarrow Y(1S)\gamma\gamma\gamma] = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

Belle preliminary
$B[Y(5S) \rightarrow Y(1D)\pi^+\pi^- \rightarrow Y(1S)\gamma\pi^+\pi^-] = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$
First particle(s) found at LHC!
Mass of $\chi_b(3P)$ centroid:

**ATLAS, 4.4 fb\(^{-1}\) @ 7 TeV**

\[ M = 10539 \pm 4 \pm 8 \text{ MeV}/c^2 \]

Confirmed by Tevatron:

**D0, 1.3 fb\(^{-1}\) @ 2 TeV**

\[ M = 10551 \pm 14 \pm 17 \text{ MeV}/c^2 \]

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**Phys.Rev. D86 (2012) 031103**
Summary

Discovery of charged bottomonia Zb, has a crucial role in S=0 bottomonium physics.

Spin averaged P wave – S wave splitting is constant at 1% level between charmonium and bottomonium.

Eta transitions will help understanding the nature of states above threshold.

Future studies will be devoted on 3P and 1D states.

Comparisons between charmonium and bottomonium keep providing important crosschecks.

감사합니다

Thank you!