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(On behalf of the Belle Collaboration)

Outline

- $h_b(nP) \rightarrow \eta_b(mS)\gamma$
- Radiative $\Upsilon(2S)$ decay
- $\Upsilon(1D)$ mass
- $R_b$ Scan
- Summary
• My talk is a tour of some of the bottomonium states, indicated by studied using the unique data set of Belle
Belle datasets

- Belle has collected most of its data at the Y(4S) resonance
  - To study various aspects of B-meson decays
  - Most celebrated result has been “CP violation in B-meson decays”

- e+e− colliders produce a particularly clean environment to study properties of the Y states.
- The entire collision energy of the initial e+e− system turns into the Y rest mass.
Observation of $h_b(nP)$

Looking for $h_b(nP)$

$Y(5S) \rightarrow h_b \pi^+ \pi^-$ reconstruction

Reconstructed, use $M_{miss}(\pi^+ \pi^-)$

$M(h_b) = \sqrt{(E_{CM} - E^{*}_{\pi^+ \pi^-})^2 - E^{*}_{\pi^+ \pi^-}^2} \equiv M_{miss}(\pi^+ \pi^-)$

PRL 108, 032001 (2012)

$\Delta M_{HF}(1P) = +0.8 \pm 1.1\text{MeV}$ consistent with zero, as expected.

$\Delta M_{HF}(2P) = +0.5 \pm 1.2\text{MeV}$

large $h_b(1,2P)$ production rate $\Rightarrow Z_b^+$ Discovery

See R. Mizuk’s talk, on 26th April
Observation of $h_b(nP)$

Looking for $h_b(nP)$

$Y(5S) \rightarrow h_b\pi^+\pi^-$ reconstruction

Reconstructed, use $M_{\text{miss}}(\pi^+\pi^-)$

$p^+ \rightarrow h_b nP$

$h_b \rightarrow \eta_b \pi^+ \pi^-$

$\gamma \gamma \gamma\pi^+ \pi^-$

$M(h_b) = \sqrt{(E_{\text{CM}} - E_{\pi^+\pi^-})^2 - E_{\pi^+\pi^-}^2} \equiv M_{\text{miss}}(\pi^+\pi^-)$

High yield of $h_b(nP)$ opens new perspective to study $\eta_b(mS)$!!
Observation of $h_b(nP) \rightarrow \eta_b(mS)\gamma$

Decay chain

$\gamma(5S) \rightarrow Z_b \pi^+$

$\rightarrow h_b(nP) \pi^+$

$\rightarrow \eta_b(mS) \gamma$

reconstruct

Use missing mass to identify signals

$\Delta M_{\text{miss}}(\pi^+\pi^-\gamma) \equiv M_{\text{miss}}(\pi^+\pi^-\gamma) - M_{\text{miss}}(\pi^+\pi^-) + M[h_b]$

- rectangular bg bands
- no correlation
 MC simulation

Signal is a cluster in the 2D plane and we determine the $h_b$ yield in bins of $\Delta M_{\text{miss}}(\pi^+\pi^-\gamma)$

Approach:

$M(\eta_b) \mapsto\quad M(\eta_b)$

$M(h_b) \mapsto\quad M_{\text{miss}}(\pi^+\pi^-), \text{GeV/c}^2$ - fit $M_{\text{miss}}(\pi^+\pi^-)$ spectra in $\Delta M_{\text{miss}}(\pi^+\pi^-\gamma)$ bins

Hadronic event selection;
continuum suppression using event shape;
$\pi^0$ veto.

Require intermediate $Z_b$: $10.59 < \text{MM}(\pi) < 10.67 \text{ GeV}$

133.4 fb$^{-1}$ Data used at $\gamma(5S)$ resonance
Re-Discovery of $\eta_b(1S)$ at Belle

$m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8$ MeV/c²

First measurement of $\Gamma = 10.8_{-3.7}^{+4.5} \text{MeV/c}^2$

B.F. $[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7_{-3.3}^{+5.6})\%$

B.F. $[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 5.7_{-3.3}^{+5.6})\%$

More precise than PDG 2012 (avg)$[9391.0 \pm 2.8 \text{MeV}]$, decreases tension with theory
First evidence of $\eta_b(2S)$ at Belle

\[ m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9} \text{ MeV/c}^2 \]

with significance (including sys.) at 4.2\(\sigma\)

\[ \text{B.F.} [h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5^{+6.8}_{-7.7})\% \]

\[ \Delta M_{\text{HF}(2S)} = 24.3^{+4.0}_{-4.5} \text{ MeV/c}^2 \]

Belle
First evidence of $\eta_b(2S)$ at Belle

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Belle

Reference: T. J. Burns
PRD 87, 034022 (2013)

Reference: S. Dobbs et. al.
PRL 109, 082001 (2012)
Observation of the $\eta_b(2S)$ Meson in $\Upsilon(2S) \rightarrow \gamma \eta_b(2S)$, $\eta_b(2S) \rightarrow$ Hadrons
and Confirmation of the $\eta_b(1S)$ Meson

Northwestern University, Evanston, Illinois 60208, USA
(Received 18 April 2012; published 24 August 2012)

The data for 9.3 million $\Upsilon(2S)$ and 20.9 million $\Upsilon(1S)$ taken with the CLEO III detector have been used to study the radiative population of states identified by their decay into 26 different exclusive hadronic final states. In the $\Upsilon(2S)$ decays, an enhancement is observed at a $\sim 5\sigma$ level at a mass of $9974.6 \pm 2.3({\text{stat}}) \pm 2.1({\text{syst}})$ MeV. It is attributed to $\eta_b(2S)$ and corresponds to the $\Upsilon(2S)$ hyperfine splitting of $48.7 \pm 2.3({\text{stat}}) \pm 2.1({\text{syst}})$ MeV. In the $\Upsilon(1S)$ decays, the identification of $\eta_b(1S)$ is confirmed at a $\sim 3\sigma$ level with $M[\eta_b(1S)]$ in agreement with its known value.

The measurement is carried out in 26 exclusive decays of the $\eta_b(2S)$ into charged hadrons.

\[
B_1 \times B_2 \equiv B_1[\Upsilon(nS) \rightarrow \gamma \eta_b(nS)] \times \sum_{i=1}^{26} B_{2i}[\eta_b(nS) \rightarrow h_i]
\]

\[
B_1 \times B_2(\eta_b(2S)) = (46.2 \pm ^{+29.7}_{-14.2} \pm 10.6) \times 10^{-6}
\]

Reminder: Our $\Delta M_{\text{HF}}(2S) = 24.3^{+4.0}_{-4.5}$ MeV/c^2

S. Dobbs’s $\eta_b(2S)$ signal is not consistent with theory as well as our measurement.
We study $\Upsilon(2S) \rightarrow \gamma (b\bar{b})$; where $(b\bar{b})$ decays hadronically (same 26 exclusive hadronic final states as mentioned in S. Dobbs et. al.)

- Following decay channels are good control samples

  $\Upsilon(2S) \rightarrow \gamma \chi_{bJ} \quad (J = 0, 1, 2)$

  and $\chi_{bJ}$ can decay to the hadronic modes (comprising charged pions, kaons, protons and $K_s$ mesons)

- Off-resonance $\Upsilon(4S)$ data [89.5 fb$^{-1}$ ~4 times larger than our $\Upsilon(2S)$ data] used for background shape study.

- Study is performed using the 25 fb$^{-1}$ data ($157.8 \times 10^6 \Upsilon(2S)$ events).

- ~17 times more data than CLEO-c’s $\Upsilon(2S)$ sample

\[ x_1 : 2(\pi^+\pi^-), 3(\pi^+\pi^-), 4(\pi^+\pi^-), 5(\pi^+\pi^-), K^+K^-\pi^+\pi^-, K^+K^-2(\pi^+\pi^-), K^+K^-3(\pi^+\pi^-), K^+K^-4(\pi^+\pi^-), 2(K^+K^-), 2(K^+K^-)\pi^+\pi^-, 2(K^+K^-)2(\pi^+\pi^-), 2(K^+K^-)3(\pi^+\pi^-), pp\pi^+\pi^-, p\bar{p}2(\pi^+\pi^-), p\bar{p}3(\pi^+\pi^-), p\bar{p}4(\pi^+\pi^-), p\bar{p}K^+K^-\pi^+\pi^-, p\bar{p}K^+K^-2(\pi^+\pi^-), p\bar{p}K^+K^-3(\pi^+\pi^-), K_{S}^0K^+\pi^+\pi^-, K_{S}^0K^+\pi^+\pi^-2(\pi^+\pi^-), K_{S}^0K^+\pi^+\pi^-3(\pi^+\pi^-), 2K_{S}^0\pi^+\pi^-, 2K_{S}^02(\pi^+\pi^-), 2K_{S}^03(\pi^+\pi^-). \]
(b\bar{b}) reconstruction:
• Impact parameter cuts
• Number of charged tracks
• Particle identification (pion, kaon, proton)

γ(2S) → γ (b\bar{b})

γ - selection
• Isolated cluster
• Energy of gamma > 22 MeV
• E9/E25 > 0.85
• Exclude endcaps

|Cosθ_T| < 0.8 : Continuum - Suppression

Simple and Straightforward !!
\( \Upsilon(2S) \rightarrow \gamma \ (b\bar{b}) \)

- More variables exploited to suppress backgrounds:
  - \( \Delta E \)
    \[
    E_{\Upsilon (2S)}^* - E_{CM}
    \]
    should peak around 0.
    \([\Delta E > -0.04 \text{ GeV} \ & \Delta E < 0.05 \text{ GeV}]\)
  - \( P_{\Upsilon (2S)}^* \)
    momentum of the \( \Upsilon (2S) \) candidate in the center-of-mass.
    should peak around 0.
    \([P_{\Upsilon (2S)}^* < 0.03 \text{ GeV/c}]\)
  - \( \theta_{\gamma (bb)} \)
    Angle between \( \gamma \) candidate and \((b\bar{b})\) in the CM Frame.
    should peak around 180\(^0\).
    \([\theta_{\gamma (bb)} > 150^0]\)
- Cut values obtained from optimization (assuming S. Dobbs et. al. B. F.)
- Multiple Candidates found at this stage is 8-10%.
- Energy-Momentum constrained kinematic fit (4C) is used to improve the resolution as well as for the best candidate selection.
$\Upsilon(2S) \rightarrow \gamma (b\bar{b})$

The background at low energy is mainly coming from beam-background, which is exponential in nature and has long tail.

(To demonstrate this, we fitted $\Upsilon(4S)$ [89.5 fb$^{-1}$] off-resonance)

[exponential+chebyshev pol.]
Large statistics available in our sample for $\chi_{bJ}$ (300-950 candidates) allows to determine precisely the $\chi_{bJ}$ masses. (with an accuracy competitive with PDG 2012).

<table>
<thead>
<tr>
<th></th>
<th>Mass $\ (\text{MeV}/c^2)$</th>
<th>Mass PDG   $\ (\text{MeV}/c^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{b0}(1P)$</td>
<td>$9859.63 \pm 0.49$</td>
<td>$9859.42 \pm 0.42 \pm 0.31$</td>
</tr>
<tr>
<td>$\chi_{b1}(1P)$</td>
<td>$9892.83 \pm 0.23$</td>
<td>$9892.78 \pm 0.26 \pm 0.31$</td>
</tr>
<tr>
<td>$\chi_{b2}(1P)$</td>
<td>$9912.00 \pm 0.34$</td>
<td>$9912.21 \pm 0.26 \pm 0.31$</td>
</tr>
</tbody>
</table>
We did not find any signal corresponding to S. Dobbs et. al. $\eta_b(2S)$ candidate!!

$N[\eta_b(2S)]$ candidate = $-29.6^{+19}_{-19}$ (negative signal yield).
We did not find any signal corresponding to S. Dobbs et. al. $\eta_b(2S)$ candidate!!

$$\mathcal{B}_1 \times \mathcal{B}_2 \equiv \mathcal{B}_1[\gamma(nS) \rightarrow \gamma \eta_b(nS)] \times \sum_{i=1}^{26} \mathcal{B}_{2i}[\eta_b(nS) \rightarrow h_i]$$

The Upper Limit on the B.F. (90% C.L.) $< 5.1 \times 10^{-6}$ (with sys.)

Reminder: $(46.2 \pm 29.7 \pm 10.6) \times 10^{-6}$ S. Dobbs et. al.
\( \Upsilon(1D) \) Mass

\[ \Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \]
\[ \rightarrow \chi_{bJ}(1P)\gamma \]
\[ \rightarrow \Upsilon(1S)\gamma \]

- Babar [PRD82(2010)111102]: \( m_{\Upsilon(1D)} = 10164.5 \pm 0.8 \pm 0.5 \) MeV/c\(^2\)
- Cleo [PRD70(2004)032001]: \( m_{\Upsilon(1D)} = 10161.1 \pm 0.6 \pm 1.6 \) MeV/c\(^2\)

\[ m_{\Upsilon(1D)} = 10164.7 \pm 1.4 \pm 1.0 \text{ MeV/c}^2 \]
\[ m_{\Upsilon(2S)} = 10023.2 \pm 1.0 \text{ MeV/c}^2 \]

coincides with PDG value \( 10023.26 \pm 0.31 \) MeV/c\(^2\)
$\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$

$\rightarrow \chi_{bJ}(1P)\gamma$

$\rightarrow \Upsilon(1S)\gamma$

- Three $\Upsilon(1D)$ states are predicted by theory
  \[ L=2, S=1 \Rightarrow J=1, 2 \text{ and } 3 \]
- We assume production of $\Upsilon_1(1D)$, $\Upsilon_2(1D)$ and $\Upsilon_3(1D)$ proportional to $(2J+1)$ i.e. 3: 5:7.
- Use B.F.s of $\Upsilon_1(1D) \rightarrow \chi_{b0}\gamma$, $\Upsilon_2(1D) \rightarrow \chi_{b1}\gamma$ and $\Upsilon_3(1D) \rightarrow \chi_{b2}\gamma$ from Kwong, Rosner PRD 38, 279 (1998)
- $B(\chi_{b0,1,2} \rightarrow \Upsilon(1S)\gamma) = 1.76\%, 33.9\% \text{ and } 19.1\%$ respectively from PDG-2012.
- $N\Upsilon_1(1D): N\Upsilon_2(1D): N\Upsilon_3(1D) = 10\%:49\%:41\%$
- Assuming only $\Upsilon_2(1D)$ and $\Upsilon_3(1D)$ contribute, (conservative assumption) we can fit the distribution to two peaks with fixed relative yields.

Splitting between $J=2$ and $J=3$ is $\Delta M < 10 \text{ MeV at } 90\% \text{ CL (with sys.)}$

Potential model expectations: 4-11MeV
Search for Ali’s $Y_b(10900)$

By definition $R_b$ is given by:

$$R_b(s) \equiv \frac{\sigma_{b\bar{b}(\gamma)}(s)}{\sigma_{\mu\mu}(s)}$$

61 points from 10.750 GeV to 11.050GeV with a step 5MeV around 50pb$^{-1}$ for each energy point

- Better statistical errors, but covers a smaller energy range compared to Babar
- $R_b$ is slightly higher by 0.0185
**Summary**

- \( h_b(nP) \rightarrow \eta_b(mS)\gamma \)
  
  \[
  m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8 \text{ MeV/c}^2 \quad \Gamma = 10.8^{+4.0}_{-3.7}^{+4.5}_{-2.0} \text{ MeV/c}^2
  \]
  
  \[
  m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9} \text{ MeV/c}^2
  \]

- \( \Upsilon(2S) \rightarrow \gamma (b\bar{b}) \)
  
  no signal found similar to S. Dobbs et. al. [attributed to \( \eta_b(2S) \)].
  
  Upper Limit on the B.F. (90% C.L.) < 5.1 \times 10^{-6}

- \( \Upsilon(1D) \) \[ NEW \]
  
  \[
  m_{\Upsilon(1D)} = 10164.7 \pm 1.4 \pm 1.0 \text{ MeV/c}^2
  \]

  Splitting between J=2 and J=3, \( \Delta M < 10 \text{ MeV at 90% CL.} \)

- No Ali’s \( Y_b(10900) \) found in \( R_b \) scan.
Backup
$\Delta M$ for $\eta_b(2S)$ and $\chi_{bJ}$ region

S. Dobbs signal MC embedded

![Graph showing $\Delta M$ for $\eta_b(2S)$ and $\chi_{bJ}$ region]