Search for $\eta_b(nS)$ at CLEO

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Bottomonium States - below threshold

It’s been 30 years since the 1st bottomonium state was discovered.

Yet, we have still not seen the ground state of the system!!

NOT seen
Experimental Status on $\eta_b(1S)$ - I

- **PDG lists (omitted from summary table)**
  
  \[ M(\eta_b(1S)) = 9300\pm20\pm20\text{MeV} \]  
  (ALEPH coll. see below).

  Most of the potential models predict
  
  \[ M(\eta_b(1S)) \sim 9.40^{+0.03}_{-0.05} \text{GeV} \]

  summarized in S. Godfrey and J. L. Rosner
  
  PRD64,074011(2001).

- **ALEPH collaboration (PLB530, 56 (2002))**
  
  - Looked for 4 and 6 charged tracks ($\pi$ and K) in 2-photon fusion processes.
  
  - Saw no events in 4-tk mode

  Saw one event (over expected bkg of $0.74\pm0.34$) in 6-tk mode.

  It looked like $K_S K \pi^+ \pi \pi^+$.

  - Provided ULs @ 95% C.L. on

  \[ \Gamma_{\gamma\gamma}(\eta_b) \times B(\eta_b(1S) \rightarrow 4 \text{ tracks}) < 48\text{eV} \]

  \[ \Gamma_{\gamma\gamma}(\eta_b) \times B(\eta_b(1S) \rightarrow 6 \text{ tracks}) < 132\text{eV} \]
Experimental Status on $\eta_b(1S)$ - II

- DELPHI collaboration (PLB634, 340 (2006))
  - Similarly, looked for 4, 6, and 8 charged tracks ($\pi$ and K) in 2-photon fusion processes.
  - Saw 0 events (1.2 bkg expected) in 4-tk mode
    - Saw 2 events (1.1 bkg expected) in 6-tk mode
    - Saw 1 event (1.5 bkg expected) in 8-tk mode
      - in the range of $9.2 \text{GeV} < M_{tk} < 9.6 \text{GeV}$.
  - Provided ULs @ 95% C.L. on
    - $\Gamma_{\gamma\gamma}(\eta_b) \times B(\eta_b(1S) \rightarrow 4 \text{ tracks}) < 190 \text{eV}$
    - $\Gamma_{\gamma\gamma}(\eta_b) \times B(\eta_b(1S) \rightarrow 4 \text{ tracks}) < 470 \text{eV}$
    - $\Gamma_{\gamma\gamma}(\eta_b) \times B(\eta_b(1S) \rightarrow 4 \text{ tracks}) < 660 \text{eV}$
SOME ways to produce $\eta_b(nS)$ at CLEO

Magnetic Dipole (M1) Transitions

- $\Gamma_{M1} \propto k^3/m_Q^2 \cdot |\langle f|j_0(kr/2)|i\rangle|^2$

- Allowed M1 ($n^3S_1 \rightarrow n^1S_0$)
  - $|\langle f|j_0(kr/2)|i\rangle| \sim 1$
  - $k$ is small
    ($\sim 60\text{MeV for } 1S \rightarrow 1S$)

- Forbidden M1 ($n^3S_1 \rightarrow m^1S_0$)
  - $|\langle f|j_0(kr/2)|i\rangle| \ll 1$
  - $k$ is large
    ($\sim 600/900\text{MeV for } 2/3S \rightarrow 1S$)
SOME ways to produce $\eta_b(nS)$ at CLEO

Through the $h_b(1P)$ just like how we discovered $h_c(1P)$

Other paths will be studied as well (see later slides)
CLEO-III detector

- Located at Cornell Electron Storage Ring
- $e^+e^-$ collisions at $\sqrt{s} \sim 10$GeV (2001~2002)

- **EM calorimeter** - Essential for photon spectroscopy
  - $\sim 8000$ CsI(Tl) crystals + photo-diodes
  - First crystal calorimeter in magnetic field (1.5T)
  - 2.2 (5)% at $E_\gamma=1(0.1)$GeV

Excellent charged particle detection

Excellent particle identification

- $dE/dx$
- Ring Imaging Cherenkov (RICH)
Data sets taken with CLEO-III detector

<table>
<thead>
<tr>
<th>Resonance</th>
<th>CLEO-III Integrated Luminosity (fb⁻¹)</th>
<th>CLEO III</th>
<th>CLEO II</th>
<th>Crystal Ball (CUSB)</th>
<th>Belle</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(1S)</td>
<td>1.0</td>
<td>21</td>
<td>1.9</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y(2S)</td>
<td>1.2</td>
<td>6</td>
<td>0.46</td>
<td>(1.3)</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Y(3S)</td>
<td>1.2</td>
<td>9</td>
<td>0.49</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Still the largest samples in the world!!

Belle and BaBar can tag (e.g.) $\pi^+\pi^-$ to reach $\Upsilon(1,2S)$ states $\rightarrow$ can avoid continuum ($B_{\pi^+\pi^-} \cdot \varepsilon_{\pi^+\pi^-} \sim$ a few %).

$\sim$30/fb by March
Search for $h_b(1P) \rightarrow \eta_b(1S) \gamma$ exclusively

\[ n^{2S+1} L_J \]

\[ \pi, \pi^0, K \ldots \text{etc} \]
\[ \Upsilon(3S) \rightarrow (\pi^0 \text{or } \pi^+\pi^-) \ h_b(1P), \ h_b(1P) \rightarrow \eta_b(1S) \gamma \]

- Similar to \( h_c \) study at CLEO
  - Predicted: \( B(\psi(2S) \rightarrow \pi^0 \ h_c) \cdot B(h_c \rightarrow \eta_c \gamma) \sim 4 \times 10^{-4} \)
    (i.e. see S. Godfrey and J.L. Rosner, PRD66,014012 (2002))
  - Measured: \( B(\psi(2S) \rightarrow \pi^0 \ h_c) \cdot B(h_c \rightarrow \eta_c \gamma) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4} \)
    based on 3M \( \psi(2S) \) sample (PRL95,102003(2005),PRD72,092004(2005))

Reconstructed \( \eta_c \) exclusively based on 15\% of \( \eta_c \) decays according to PDG2007

- We have \( \sim 6M \ Upsilon(3S) \) sample.
- \( B(\Upsilon(3S) \rightarrow \pi^0 \ h_b) \cdot B(h_b \rightarrow \eta_b \gamma) \sim 4 \times 10^{-4} \)
- Not enough phase space between \( M(\Upsilon(2S)) \) and \( M(h_b) \) assuming \( M(h_b) = 9.9\text{GeV} \) (predicted to be \( \sim 9900 \pm 4\text{MeV} \), see the above summary of Godfrey and Rosner).

Can we detect 7\% of \( \eta_b \) decays?
\( \Upsilon(3S) \rightarrow (\pi^0 \text{ or } \pi^+\pi^-) \ h_b(1P), \ h_b(1P) \rightarrow \eta_b(1S) \ \gamma \)

- Between \( M(\Upsilon(3S)) \) and \( M(h_b) \), there IS enough phase space to produce two \( \pi \) and we don’t have to violate isospin conservation!.
- Predictions vary: \( B(\Upsilon(3S) \rightarrow \pi^+\pi^- \ h_b) \cdot B(h_b \rightarrow \eta_b \ \gamma) \sim 4 \times 10^{-4} \sim 8 \times 10^{-3} \) (i.e. see S.Godfrey and J.L.Rosner, PRD66,014012 (2002))
- Also the transition photon is detectable.\[ E_\gamma \sim 500 \text{MeV from } h_c \rightarrow \eta_c \ \gamma \text{ likewise } E_\gamma \sim 490 \text{MeV from } h_b \rightarrow \eta_b \ \gamma \] assuming \( M(h_b)=9.9 \text{GeV} \) and \( M(\eta_b)=9.4 \text{GeV} \).

This is all good news. BUT ……
$\Upsilon(3S) \rightarrow (\pi^0 \text{ or } \pi^+\pi^-) h_b(1P), h_b(1P) \rightarrow \eta_b(1S) \gamma$

- Higher particle average multiplicities (neutrals) in $\Upsilon$ data makes much more difficult to isolate a photon (and larger relative production of continuum).

- $E_\gamma = 483 \text{MeV}$ from $\Upsilon(3S) \rightarrow \gamma \chi_{b}(1P_0)$ might make things worse since $E_\gamma \sim 490 \text{MeV}$ from $h_b \rightarrow \eta_b \gamma$.

Other hindered E1 transistions.
5 photon lines overlapped.
Search for $\Upsilon(nS) \rightarrow \eta_b(mS) \gamma$ exclusively

\[ n^{2S+1} L J \]

\[ \pi, \pi^0, K... etc \]
\( \Upsilon(nS) \rightarrow \eta_b(mS)\gamma \)

- **RECALL:** \( \Gamma_{M1} \propto k^3/m^2_Q \cdot |\langle f|j_0(kr/2)|i\rangle|^2 \)
  - **Allowed M1** \( (n^3S_1 \rightarrow n^1S_0) \)
    - \( |\langle f|j_0(kr/2)|i\rangle| \sim 1 \)
    - \( k \) is small (~60MeV for \( 1S \rightarrow 1S \))
  - **Forbidden M1** \( (n^3S_1 \rightarrow m^1S_0) \)
    - \( |\langle f|j_0(kr/2)|i\rangle| \sim 0 \)
    - \( k \) is large (~600/900MeV for \( 2/3S \rightarrow 1S \))
    - Could the larger \( k^3 \) factor compensate the smaller \( |\langle f|j_0(kr/2)|i\rangle|^2 \) in cases of \( 3S \rightarrow 1S \) and \( 2S \rightarrow 1S \)?

- CLEO has looked for \( \Upsilon(nS) \rightarrow \eta_b(mS)\gamma \) inclusively.
  No signals were seen, set Uls @ 90% C.L. (PRL94,032001(2005))
  \( \rightarrow B(\Upsilon(2S) \rightarrow \eta_b(1S)\gamma) < 5.1 \times 10^{-4} \)
  \( B(\Upsilon(3S) \rightarrow \eta_b(1S)\gamma) < 4.3 \times 10^{-4} \)
  \( B(\Upsilon(3S) \rightarrow \eta_b(2S)\gamma) < 6.2 \times 10^{-4} \)

- Predictions vary: \( B(\Upsilon(2,3S) \rightarrow \eta_b(1S)\gamma) \sim 10^{-6} \sim 10^{-3} \)
\( \Upsilon(nS) \to \eta_b(mS) \gamma \)

- Sensitivity to **inclusive** \( \Upsilon(1S) \to \eta_b(1S) \gamma \) limited due to the large background in \( E_\gamma < 100 \text{MeV} \) region.

- At CLEO, we are currently investigating **BOTH** allowed and **forbidden** M1 transitions exclusively.

Which \( \eta_b \) decay modes should we exclusively look for?
\[ \Upsilon(nS) \rightarrow \eta_b(mS) \gamma \]

- The \( \eta_c \)-like modes found in PDG? There are SOME more \( \eta_c \)-like modes NOT found in PDG (see the next slide).
- \( M(\eta_b) > \sim 3 \times M(\eta_c) \)
  \( \Rightarrow \eta_b \) should have higher average multiplicities.
- We also see significant \( \chi_{cJ} \) peaks produced via \( \psi(2S) \rightarrow \chi_c(1P_J) \gamma \) for these exclusive modes.

How about \( \chi_b(1,2P_J) \)-like modes?
The largest yields!!??

$\psi(2S) \rightarrow \eta_c(1S) \gamma$

See Ryan Mitchell’s QWG07 talk for more detail

Preliminary

$E_{\gamma}$ in GeV from $\psi(2S) \rightarrow \eta_c(1S) \gamma$

$\star$ = NOT listed in PDG
$\Upsilon(nS) \rightarrow \eta_b(mS) \gamma$

Currently trying to conduct the following 3 tests

- **Test 1:**
  - We know $B(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) < 0.00051$ (0.00043 for $\Upsilon(3S)$ decays).
  - Assuming $B(\Upsilon(2S) \rightarrow \gamma \chi_{bJ}) = 6\%$ for each $J$
    (3.8, 6.9, 7.15\% for $J=0,1,2$)
  and assuming efficiencies and branching ratios of events from
    $\Upsilon(2S) \rightarrow \gamma \chi_{bJ}$, $\chi_{bJ} \rightarrow X$
  are the same as the ones from
    $\Upsilon(2S) \rightarrow \gamma \eta_b$, $\eta_b \rightarrow X$
  for the same exclusive modes, $X$,
  then we should see one $\eta_b$ event while seeing $\sim 100 \chi_{bJ}$ events
  (for each $J$).

Can we see *significant* $\chi_b(nP_J)$ signals *exclusively*?
(which, itself, is interesting…)
Then, choose modes based on $\chi_b(1,2P_J)$ signals.
\( \Upsilon(nS) \rightarrow \eta_b(mS) \gamma \)

- Test 2:
  - We have measured a hindered E1 transition;
    \[ B(\Upsilon(3S) \rightarrow \chi_b(1P_0) \gamma) = (3.0 \pm 0.4 \pm 1.0) \times 10^{-3} \]
    (PRL94,032001(2005)).
  - What we are looking for is \( \sim 10^{-4} \) at most.
  - Better be able to see the transition
    \( \Upsilon(3S) \rightarrow \chi_b(1P_J) \gamma, \chi_b(1P_J) \rightarrow \text{exclusives} \)
    (which, itself, is interesting ... Recall the overlapped photon peaks shown earlier).
$\Upsilon(nS) \rightarrow \eta_b(mS) \gamma$

**Test 3: Consistency check ("IF" we pass Test 1 and 2)**
- Do we see an enhancement around invariant mass of $9400\pm50\text{MeV}$?
- Do we see similar enhancements in all of the $\Upsilon(1,2,3S)$ data with the same mass (in $\Upsilon(1S)$, there could be an additional experimental challenge to detect $\sim60\text{MeV}$-photon)?
- Do we see a similar enhancement with the same mass with the following chains:
  - $\Upsilon(3S) \rightarrow \pi^0 h_b, h_b \rightarrow \eta_b \gamma, \eta_b \rightarrow$ exclusives
  - $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b, h_b \rightarrow \eta_b \gamma, \eta_b \rightarrow$ exclusives
  - $\Upsilon(3S) \rightarrow \chi_{b}(2P_0) \gamma, \chi_{b}(2P_0) \rightarrow \eta_b \eta, \eta_b \rightarrow$ exclusives

M.B. Voloshin M.P.L.A19,2895 (2004) predicts $B(\chi_{b}(2P_0) \rightarrow \eta_b \eta) \sim 10^{-3}$. 
Summary/Comments

• Currently, we are working on:
  – $\Upsilon(nS) \rightarrow X \gamma, X \rightarrow$ exclusives, ($n=1,2, \text{ and } 3$)
    where $X=\eta_b(mS), \chi_b(mP)$
  – $\Upsilon(3S) \rightarrow \pi^0/\pi\pi \ h_b, h_b \rightarrow \eta_b\gamma$

• Potential excitement in the near future
  – BaBar plans to have $\sim 30/fb$ data taken at $\Upsilon(3S)$ by March. Is the boosted frame an issue?
  – Belle already has $11M \ Upsilon(3S)$ decays.
  – If Super B factory could devote a few days ($\sim 1/ab$???) to run on lower resonances, such data should allow us to do precision study on $\eta_b$ properties.