Upsilon(1S,2S,3S) Studies at CLEO

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Studies of $\Upsilon(1S,2S,3S)$: Outline

- Motivation for studying Quarkonium
- CLEO III detector, data sample and quality
- Measurement of $B_{\mu\mu}(\Upsilon(nS))$ ($n=1,2,3$)
- Hadronic transitions within Upsilon states
- E1 and M1 Photon transitions
- Upsilon decays to Charmonium states
- Conclusion
Motivation for Studying Quarkonium

- Simplest strongly interacting system
- QCD equivalent of positronium
- Non-relativistic for heavy quarks (Q\bar{Q})
  \[ Q=c: \quad \beta^2 \sim 0.25; \quad Q=b: \quad \beta^2 \sim 0.08 \]
- Tests potential models, \[ V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + k r \]
- Tests Lattice QCD calculations
The Upsilon System: Bottomium

Rich spectroscopy,
many transitions - hadronic, photonic
Y(1S,2S,3S) directly produced in e+e- annihilation
CLEO III Data Sample on $\Upsilon(1S, 2S, 3S)$

Orders of magnitude improvement in statistics, plus a much more powerful detector!
The CLEO III Detector
$B_{\mu\mu}$ for the $\Upsilon$ States

- Importance beyond knowing $B(\Upsilon(nS) \rightarrow \mu^+\mu^-)$
- Needed to get $\Gamma_{tot}$ for narrow resonances from $\Gamma_{ee}$
- CLEO hopes to measure $\Gamma_{ee}$ to a few percent
- Many analyses use the $\mu^+\mu^-$ final state for cleanliness
- $B_{\mu\mu}$ affects many branching fractions and partial widths
$B_{\mu\mu}$ for the $\Upsilon$ States

**Measurement of $B(\Upsilon(nS) \to \mu^+\mu^-)$**

Leptonic ($\Gamma_{ll}$) and total widths ($\Gamma$) of $\Upsilon(n^3S_1)$ resonances are not very well established. They have 4 - 16% relative errors.

$\Gamma$ and $\Gamma_{ee}$ are used in many PQCD calculations.

Precise measurement of $B(l^+l^-)$ allows to determine $\Gamma$ of $\Upsilon(nS)$ precisely (precise $\Gamma_{ee}$ measurement is also needed, expected soon from CLEO):

$$\Gamma = \Gamma_{ll} / B_{ll} - \Gamma_{ee} / B_{\mu\mu} \quad \text{(assuming lepton universality)}$$

$\Rightarrow$ Measure decay rate to muon pairs relative to hadronic decay rate:

$$\overline{B}_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_{had}} = \frac{N(Y \to \mu^+\mu^-)}{\epsilon_{\mu\mu}} / \frac{N(Y \to \text{hadrons})}{\epsilon_{had}}$$

$$B_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_{had}} = \frac{\Gamma_{\mu\mu}}{\Gamma_{had}(1+3\Gamma_{\mu\mu}/\Gamma_{had})} = \frac{\overline{B}_{\mu\mu}}{1+3\overline{B}_{\mu\mu}}$$
Large signals in $m_{\mu\mu}/\sqrt{s}$ after continuum subtraction at the $\Upsilon(1S)$, $\Upsilon(2S)$, and even $\Upsilon(3S)$ ... 

\[
B_{\mu\mu}(\Upsilon(nS))
\]

- Data
- MC with $\mu$ FSR
- MC without $\mu$ FSR

... and details such as muon FSR allow for high precision.
\section*{\textbf{$B_{\mu\mu}$ for the Bound $\Upsilon$ States}} [CLEO, submitted to PRL]

<table>
<thead>
<tr>
<th>$\Upsilon$ State</th>
<th>$B_{\mu\mu}$ (%)</th>
<th>$\Gamma_{\text{tot}}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CLEO preliminary</td>
<td>PDG</td>
</tr>
<tr>
<td>$\Upsilon$(1S)</td>
<td>2.53 ± 0.02 ±0.05</td>
<td>2.48 ± 0.06</td>
</tr>
<tr>
<td>$\Upsilon$(2S)</td>
<td>2.11 ± 0.03 ±0.05</td>
<td>1.31 ± 0.21</td>
</tr>
<tr>
<td>$\Upsilon$(3S)</td>
<td>2.44 ± 0.07 ±0.05</td>
<td>1.81 ± 0.17</td>
</tr>
</tbody>
</table>

\textbf{Few \% precision reached!}

$B_{\mu\mu}(\Upsilon(2,3S))$

significantly higher than prior results

Await CLEO $\Gamma_{\text{ee}}$!

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{plot.png}
\end{figure}
Hadronic Transitions between Upsilon States

Di-Pion Transitions from $\Upsilon(3S)$

Preliminary branching ratio measurements for $\Upsilon(2S)$ and $\Upsilon(3S)$:

- $B(\Upsilon(3S) \rightarrow \pi^0\pi^0 \Upsilon(2S)) = 2.02 \pm 0.18 \pm 0.38 \%$
- $B(\Upsilon(3S) \rightarrow \pi^0\pi^0 \Upsilon(1S)) = 1.88 \pm 0.08 \pm 0.31 \%$

$\Upsilon(3S) \rightarrow \pi^0\pi^0 \Upsilon(2S)$:
- $\pi^0\pi^0$ effective mass spectrum has a shape consistent with several theoretical predictions

$\Upsilon(3S) \rightarrow \pi^0\pi^0 \Upsilon(1S)$:
- $\pi^0\pi^0$ effective mass spectrum has “double humped” shape, also observed in the charged pion transitions
NEW: Observation of $\chi_b(2P) \rightarrow \omega \Upsilon(1S)$

New $\Upsilon$ hadronic transition - not $\pi\pi$!

First hadronic transition for $\chi_b$ states!

Fully reconstructed exclusive channel: Cascade starts with E1 $\gamma$ from $\Upsilon(3S)$; ends with $\Upsilon(1S)$ to lepton pairs

Preliminary results reported in 2003; now final, with full $\Upsilon(3S)$ data sample
\[ \chi_b(2P) \rightarrow \omega \Upsilon(1S) \]

**Final Results:**

\[ B(\chi_{b1}' \rightarrow \omega \Upsilon(1S)) = (1.63^{+0.35}_{-0.31}^{+0.16}_{-0.15})\% \]
\[ B(\chi_{b2}' \rightarrow \omega \Upsilon(1S)) = (1.10^{+0.32}_{-0.28}^{+0.11}_{-0.10})\% \]

J = 0 kinematically forbidden!

Roughly equal for J = 1 and 2

\( r_{2/1} \) predicted to be \( 1.3 \pm 0.3 \)

[Voloshin - hep-ph/0304165]

Very large rate considering limited phase space!

[hep-ex/0311043, accepted by PRL]
E1 and M1 Photon Transitions

Typical $\lambda_\gamma \sim 0.3$-2fm ≥ mean quark separation ~0.3~0.8fm

Lowest multipoles dominate:

E1: $\Delta L=1, \Delta S=0$
M1: $\Delta L=0, \Delta S=1$

($\Gamma_{M1} \ll \Gamma_{E1}$)

Mass splitting are very similar between cc and bb systems

→ The responsible inter-quark force is flavor independent.
Detecting Photon Transitions

- **EM calorimeter** - Essential for photon spectroscopy
  - ~8000 CsI(Tl) crystals + photodiodes
  - First crystal calorimeter in magnetic field
- Excellent charged particle detection
- Large solid angle coverage

<table>
<thead>
<tr>
<th>Detector</th>
<th>Calorimeter crystals</th>
<th>$\sigma_{E\gamma}$ resolution at $E\gamma=100$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO III</td>
<td>CsI(Tl)</td>
<td>4.5 MeV</td>
</tr>
<tr>
<td>CUSB II</td>
<td>BGO</td>
<td>4.2 MeV</td>
</tr>
<tr>
<td>Crystal Ball</td>
<td>NaI(Tl)</td>
<td>4.8 MeV</td>
</tr>
<tr>
<td>BESII</td>
<td>Not a crystal calorimeter</td>
<td>70 MeV</td>
</tr>
</tbody>
</table>
**Photon Transitions**

**Analysis procedure**

- Same photon selection as in \(\psi(2s)\) analysis (veto tracks pointing at shower, E9/E25, suppress hot crystals)
- Suppress photons from \(\pi^0 (\cos\theta_{\gamma\gamma} > 0.7)\) for analysis of high energy photons only
- Use \(\Upsilon(1S) + \text{continuum} + \text{(low order polynomial)}\) for BKG parametrization (\(E_\gamma < 200\text{MeV}\))

\[
\Upsilon(2S) \rightarrow \chi_b(1P_J) \gamma
\]

\[
\Upsilon(3S) \rightarrow \chi_b(2P_J) \gamma
\]

\[
\Upsilon(3S) \rightarrow \chi_b(1P_J) \gamma
\]

Total fitted background

Fitted \(\Upsilon(1S)\) spectrum

Fitted continuum spectrum
Photon Transitions

\( \Upsilon(2S) \rightarrow \chi_b(1P_J) \gamma \) and \( \Upsilon(3S) \rightarrow \chi_b(2P_J) \gamma \)

BKG = \( \Upsilon(1S) \) + continuum + 0\(^{th}\) order polynomial

\( \Upsilon(1D_J) \rightarrow \chi_b(1P_J) \gamma \)

\( \Upsilon(2S) \rightarrow \chi_b(1P_J) \gamma \)
\[ \Upsilon(3S) \to \chi_{bJ}(1P_J) \gamma \]

We were able to extract
\[ \text{BR}(\Upsilon(3S) \to \chi_{b}(1P_0) \gamma) \]
whose photon peak is isolated.

Notice also that there is no significant enhancement around \(E \sim 350\,\text{MeV}\) which would correspond to
\[ \Upsilon(3S) \to \eta_b(2S) \gamma \]
Search for $\eta_b(1^{1S_0})$, $\eta_b(2^{1S_0})$

Hindered M1 transitions

Rates strongly suppressed compared to E1

Also, masses of singlet states not known experimentally
Fitting to $\Upsilon(3S) \rightarrow \eta_b(1S) \gamma$ and $\Upsilon(2S) \rightarrow \eta_b(1S) \gamma$

The UL's are looser in lower energy region due to higher background (dominated by $\pi^0$'s)
• **Test potential model predictions for** $\Gamma_{M1}$

Models from the compilation by Godfrey & Rosner PR D64, 074011 (2001); Ebert, Faustov, and Galkin, PRD67, 014027(2003); Lahde NP A714, 183(2003) [scaled here by phase-space]

• **Many calculations are ruled out!**
• Test potential model predictions for $\Gamma_{M1}$
### Results on E1 Transitions in the Upsilon System

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BR}(\Upsilon' \to \chi_{b0} \gamma) )</td>
<td>3.75±0.12±0.47%</td>
<td>3.4±0.5±0.6 %</td>
<td>3.8±0.6 %</td>
</tr>
<tr>
<td>( \text{BR}(\Upsilon' \to \chi_{b1} \gamma) )</td>
<td>6.93±0.12±0.41%</td>
<td>6.9±0.5±0.9 %</td>
<td>6.8±0.7 %</td>
</tr>
<tr>
<td>( \text{BR}(\Upsilon' \to \chi_{b2} \gamma) )</td>
<td>7.24±0.11±0.40%</td>
<td>7.4±0.5±0.8 %</td>
<td>7.0±0.6 %</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon' \to \chi_{b0} \gamma) )</td>
<td>162.56±0.19±0.42MeV</td>
<td>162.0±0.8±1.2 MeV</td>
<td>162.1±1.0 MeV</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon' \to \chi_{b1} \gamma) )</td>
<td>129.58±0.09±0.29MeV</td>
<td>128.8±0.4±0.6 MeV</td>
<td>129.8±0.5 MeV</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon' \to \chi_{b2} \gamma) )</td>
<td>110.58±0.08±0.30MeV</td>
<td>110.8±0.3±0.6 MeV</td>
<td>110.1±0.5 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>This measurement</th>
<th>CLEO2 (1991)</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BR}(\Upsilon'' \to \chi_{b0} \gamma) )</td>
<td>6.77±0.20±0.65%</td>
<td>4.9^{+0.3}_{-0.4}±0.6 %</td>
<td>5.4±0.6 %</td>
</tr>
<tr>
<td>( \text{BR}(\Upsilon'' \to \chi_{b1} \gamma) )</td>
<td>14.54±0.18±0.73%</td>
<td>10.5^{+0.3}_{-0.2}±1.3 %</td>
<td>11.3±0.6 %</td>
</tr>
<tr>
<td>( \text{BR}(\Upsilon'' \to \chi_{b2} \gamma) )</td>
<td>15.79±0.17±0.73%</td>
<td>13.5±0.3±1.7 %</td>
<td>11.4±0.8 %</td>
</tr>
<tr>
<td>( \text{BR}(\Upsilon'' \to \chi_{b0} \gamma) )</td>
<td>0.30±0.04±0.10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon'' \to \chi_{b0} \gamma) )</td>
<td>121.55±0.16±0.46MeV</td>
<td>122.3±0.3±0.6 MeV</td>
<td>122.8±0.5 MeV</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon'' \to \chi_{b1} \gamma) )</td>
<td>99.15±0.07±0.25MeV</td>
<td>99.5±0.1±0.5 MeV</td>
<td>99.90±0.26 MeV</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon'' \to \chi_{b2} \gamma) )</td>
<td>99.08±0.17±0.34MeV</td>
<td>86.09±0.30±0.29MeV</td>
<td>86.64±0.23 MeV</td>
</tr>
<tr>
<td>( E_\gamma(\Upsilon'' \to \chi_{b2} \gamma) )</td>
<td>86.04±0.06±0.27MeV</td>
<td>86.4±0.1±0.4 MeV</td>
<td>86.64±0.23 MeV</td>
</tr>
<tr>
<td>From excl. (CBX02-20)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
E1 Transitions: Impact of CLEO III Results

Weight in new world average:

- Significantly improved errors (systematics dominated)

Excellent agreement between CLEO3 and previous measurements of photon energies and branching ratios

\[
\Upsilon(2S) \rightarrow \chi_{bJ}(1P_2) \gamma
\]
E1 Transitions: Impact of CLEO III Results

\[ \Upsilon(2S) \rightarrow \chi_{bJ}(1P_1) \gamma \]
E1 Transitions: Impact of CLEO III Results

\[ \gamma(2S) \rightarrow \chi_{bJ}(1P_0) \gamma \]
$\Upsilon(3S) \rightarrow \chi_{bJ}(2P_2) \gamma$
E1 Transitions:

Fine splitting in 1P and 2P

The fine structure splitting can be quantified by \( r = \frac{m_2 - m_1}{m_1 - m_0} \)

\( r \) gives properties of Lorentz transformation (scalar and/or vector) of the confining potentials.

<table>
<thead>
<tr>
<th></th>
<th>CLEOIII</th>
<th>CLEO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r(1P) )</td>
<td>0.57±0.01±0.01</td>
<td>0.54±0.02±0.02</td>
</tr>
<tr>
<td>( r(2P) )</td>
<td>0.58±0.01±0.01</td>
<td>0.57±0.01±0.01</td>
</tr>
</tbody>
</table>

- Our results indicate that there is no difference between the different radial excitations of the P waves in bb.
The L=2 ("D") States in Quarkonium

ψ(3770): $^3S_1 - ^3D_1$ mixing? Molecule?

ϒ(1D): stable - tests models and LQCD at high L !!
Photon Transitions to $\Upsilon(1D)$ [CLEO]

Four $\gamma$ cascade; exclusive $\Upsilon(1S)$ channel

Background thru $2^3S_1$

First reported at ICHEP02 with 80% of data. Now final

Accepted by PRD [hep-ex/0404021]
Final $\Upsilon(1D)$ Analysis Results [CLEO]

$>10 \sigma$ significance

$M = 10161.1 \pm 0.6 \pm 1.6$ MeV

Consistent with $1^3D_2$

$\mathcal{B}(\Upsilon(3S) \to \gamma_1 \gamma_2 \gamma_3 \gamma_4 ll) = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

Rate consistent with theory estimates

[hep-ex/0404021; accepted by PRD]
“D” State Impact on LQCD

Ratio = LQCD/Expt

Quenched  Unquenched ($n_f=3$)

[CTH Davies et al., PRL 92:022001 (2004)]

[Courtesy: G.P. Lepage]
$\Upsilon(1D)$: What is NOT seen !!!

Search for $\Upsilon(1D) \rightarrow \pi^+\pi^- \Upsilon(1S)$

Large signal from $\Upsilon(2S)$ is consistent with known rates

No events observed from $\Upsilon(1D)$; upper limits set

Limits $\sim 7$ times lower than predicted by Kuang-Yan model; $\sim 3$ times higher than Ko model

[hep-ex/0404021]  


Also see no evidence for enhancement of $\Upsilon(1D) \rightarrow \eta \Upsilon(1S)$ as postulated by Voloshin [PL B562, 68 (2003)]
Upsilon Decay to Charmonium: $\Upsilon(1S) \rightarrow (c\bar{c})X$

- onia production and onia decay
- test of color-octet v. color-singlet models
- similar rate predictions: $B \sim 6 \times 10^{-4}$
- very different momentum spectra
- may have some relevance to $cccc$ production


Upsilon(1S) Decay to Charmonium

The $J/\psi$ Signal

All events passing cuts for $\mu^+\mu^-$ and for $e^+e^-$

$\mu^+\mu^-$ events binned in $x \equiv p_{J/\psi}/p_{\text{max}}$
\( \Upsilon(1S) \rightarrow J/\psi X \)

\( \frac{p}{p_{\text{max}}} \) much too soft for \textit{octet} model

\[ B(\Upsilon(1S) \rightarrow J/\psi X) = (6.4 \pm 0.4 \pm 0.6) \times 10^{-4} \]

This includes feed-down from other charmonia

Rate consistent with either \textit{octet} or \textit{singlet} model

Production and helicity angular distributions also determined
\( \Upsilon(1S) \rightarrow (c\bar{c}) X \)

Also: first observation of \( \psi'X \) ...

\[ B(\Upsilon \rightarrow \psi'X)/B(\Upsilon \rightarrow J/\psi X) = (41 \pm 11 \pm 8)\% \]

... and evidence for the two \( \chi_c \) states with large \( \Gamma_{E1} \)

\[ B(\Upsilon \rightarrow \chi_{c2}X)/B(\Upsilon \rightarrow J/\psi X) = (52 \pm 12 \pm 9)\% \]
\[ B(\Upsilon \rightarrow \chi_{c1}X)/B(\Upsilon \rightarrow J/\psi X) = (35 \pm 8 \pm 6)\% \]

All larger than the octet predictions.
$\Upsilon(1S)$ Decay to Charmonium (hep-ex/0407030)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Branching Ratio</th>
<th>Feed-down to $J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>$0.41 \pm 0.11 \pm 0.08$</td>
<td>$0.24 \pm 0.06 \pm 0.05$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$&lt;7.4$</td>
<td>$&lt;0.082$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>$0.35 \pm 0.08 \pm 0.06$</td>
<td>$0.11 \pm 0.03 \pm 0.02$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>$0.52 \pm 0.12 \pm 0.09$</td>
<td>$0.10 \pm 0.02 \pm 0.02$</td>
</tr>
</tbody>
</table>

The issue of color octet versus color singlet remains unresolved. The ball is back in the theorist’s court.

Suggestion to Fleming, et al., that they apply same softening mechanism they used for continuum production.

More experimentation suggested: Perhaps search for $D\bar{D}$ in association with charmonium, in $e^+e^-$ and at CDF/D0.
Summary

- Upsilon Spectroscopy revitalized after ~20 years!
- Vastly increased data sample + CLEO III detector!
- Precision scans, \( B(\mu\mu) \), \( \Gamma(\text{tot}) \) of \( \Upsilon(1S,2S,3S) \)
- Improved precision in dipion transitions
- First observation of internal \( \omega \) transition
- First observation of the 1D \( (L=2) \) state
- Precision measurement of E1 photon transitions
- Meaningful upper limits on hindered M1 transitions
- Precision measurements of \( \Upsilon(1S) \) decay to (cc)
- Generated considerable theoretical interest:
  potential models, LQCD, color octet/color singlet

...and, by the way, we also do Charmonium!
Join the QWG! (meets next week in Beijing!)
Backup slides
News on the QQ Spin-Singlets

\[ \mathcal{J}^{PC} = 0^{-+} \text{ (}{\eta}'\text{s}) \text{ and } 1^{+-} \text{ (}{h}'\text{s}) \]
Production of $Q\bar{Q}$ Spin-Singlets:

... as well as hadro-production which is the most egalitarian!
**QQ Spin-Singlets:**

- $b\bar{b}$ ($\eta_b$'s and $h_b$): limits from CLEO in ’03 ... no news
- $h_c$ ($^{1}P_1$, 1$^{+-}$): not yet (maybe that is news?)
- $\eta_c$ ($^{1}S_0$, 0$^{-+}$): Ground state of charmonium
- Still only ~30% of decays known ... some updates
- New publ’d mass determinations ... no big shifts
- Seen by CLEO in $\psi' \rightarrow \gamma\eta_c$ (>8$\sigma$) [LP03:hep-ph/0311243]
- See QWG Yellow Report for up-to-date information