Bottomonium Decays at CLEO

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The Detector and Upsilon Data Sets

Dedicated $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ runs (Nov 2001 – Dec 2002).

~21 x 10^6
~9 x 10^6
~6 x 10^6
CLEO III Upsilon Topics

- \( \Upsilon(4S) \rightarrow B\bar{B} \)
- \( \Upsilon(nS) \rightarrow ggg, ggy, q\bar{q} \)
- \( \Upsilon(nS) \rightarrow \Upsilon(mS)X, \chi_bX, \ldots \)
- \( e^+e^- \rightarrow q\bar{q} \)
- \( \Upsilon(nS) \rightarrow ee, \mu\mu, \tau\tau \)

- Anti-deuteron production in \( \Upsilon(nS) \) decays and the nearby continuum.
- Inclusive production \( \Upsilon(1S) \rightarrow \eta'X \).
- Upsilon radiative decays:
  - Observation of exclusive modes: \( \gamma\pi\pi, \gammaKK \).
  - Search for \( \Upsilon(1S) \rightarrow \gamma\pi^0\pi^0, \eta\eta, \gamma\pi^0\eta \).
  - Search for \( \Upsilon(1S) \rightarrow \gamma\eta, \gamma\eta' \).
  - UL on multi-body modes (\( \geq 4 \) charged tracks).
  - Comparison of inclusive hadron production in gluon-rich and quark environment.
Anti-Deuteron in Upsilon Decays

- Anti-deuteron production has been observed in many different kinds of hadronization processes.
- ARGUS observed anti-deuteron in \( \Upsilon(1S) \) decays. OPAL set an upper limit in Z decays.
- The production can be explained by coalescence model and a model based on string calculation. The basic idea is that an anti-proton and an anti-neutron are produced nearby in phase space to form an anti-deuteron.
- CLEO has a factor ~40 more \( \Upsilon(1S) \) than ARGUS to make a more precise measurement.
- The main PID tool is \( \text{dE/dX} \) with RICH info also used.
- CLEO measured production in momentum range (0.45 – 1.45) GeV/c and use a model dependent extrapolation for unmeasured region.
The production BR per direct $\Upsilon(1S) \rightarrow ggg, gg\gamma$ decays is

$$B^{dir}(\Upsilon(1S) \rightarrow \bar{d}X) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}$$

The overall BR per $\Upsilon(1S)$ is

$$B(\Upsilon(1S) \rightarrow \bar{d}X) = (2.86 \pm 0.19 \pm 0.21) \times 10^{-5}$$

The production in $\Upsilon(2S)$ is

$$B(\Upsilon(2S) \rightarrow \bar{d}X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}$$

Removing contribution of $\Upsilon(2S) \rightarrow \Upsilon(1S)X$, and $\Upsilon(2S) \rightarrow ggg, gg\gamma, q\bar{q}$, CLEO set 90% CL limit

$$B(\gamma\kappa_{b1,2,0} \rightarrow \bar{d}X) < 1.09 \times 10^{-4}$$

The production rate upper limit in $\Upsilon(4S)$ is

$$B(\Upsilon(4S) \rightarrow \bar{d}X) < 1.31 \times 10^{-5}$$

Continuum production cross section at $\sqrt{s}=10.5$ GeV

$$B(e^+e^- \rightarrow \bar{d}X) < 0.031 \text{ pb}$$

Deuteron production is enhanced in ggg, gg\gamma process.
Inclusive $\Upsilon(1S) \rightarrow \eta' X$

- The unexpectedly large $\beta (B \rightarrow \eta' X_S)$ with $P_{\eta'} > 2$ GeV was observed by CLEO and confirmed by BaBar.

\begin{align*}
\text{CLEO} : & (6.2 \pm 1.6 \pm 1.3^{+0.0}_{-1.5}) \times 10^{-4} \\
\text{BaBar} : & (3.9 \pm 0.8 \pm 0.5 \pm 0.8) \times 10^{-4}
\end{align*}

- Within SM, a possible explanation is the large $g^* \rightarrow g \eta'$ coupling in $b \rightarrow sg$ penguin diagram \((\text{Atwood} \ & \text{&} \ \text{Soni})\).

- Such enhancement should present in $\Upsilon(1S)$ decays \((\text{Kagan, Atwood} \ & \text{&} \ \text{Soni})\).

- CLEO II measured $\beta (\Upsilon(1S) \rightarrow ggg \rightarrow \eta' X) = (1.9 \pm 1.1 \pm 0.2) \times 10^{-4}$ for $E_{\eta'}/E_{\text{beam}} > 0.7$, ruled out a class of form factors characterized by a weak $q^2$ dependence. Higher precision is needed for more model tests.
### Inclusive $\eta'$ Production In $\Upsilon(1S)$ Data

\[ \eta' \rightarrow \eta \pi^+ \pi^-, \eta \rightarrow \gamma\gamma \]

<table>
<thead>
<tr>
<th></th>
<th>All Z</th>
<th>$Z &gt; 0.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$n \equiv \frac{N(\Upsilon(1S) \rightarrow ggg \rightarrow \eta'X)}{N(\Upsilon(1S) \rightarrow ggg)}$</td>
<td>$(3.2 \pm 0.2 \pm 0.2)%$</td>
</tr>
<tr>
<td>$b$</td>
<td>$n \equiv \frac{N(\Upsilon(1S) \rightarrow q\bar{q} \rightarrow \eta'X)}{N(\Upsilon(1S) \rightarrow q\bar{q})}$</td>
<td>$(3.8 \pm 0.2 \pm 0.3)%$</td>
</tr>
<tr>
<td>$c$</td>
<td>$n \equiv \frac{N(\Upsilon(1S) \rightarrow \eta'X)}{N(\Upsilon(1S))}$</td>
<td>$(3.0 \pm 0.2 \pm 0.2)%$</td>
</tr>
</tbody>
</table>

### Graphs

- **a)** $\Upsilon(1S) \rightarrow ggg^*$
- **b)** $\Upsilon(1S) \rightarrow q\bar{q}$
- **c)** $\Upsilon(1S) \rightarrow \eta'X$

$Z = \frac{E_{\eta'}}{E_{\text{beam}}}$

10/31/06

Jianchun Wang
The measured spectrum is not well described by existing models. The observed $B \rightarrow \eta' \chi_S$ is unlikely to be explained by an enhanced $g^* g \eta'$ form factor. An explanation outside the realm of SM or an improved understanding of non-perturbative QCD effects may be needed.
In Upsilon two-body radiative decays, the two gluons hadronize into a meson or form a glueball.

These decays are theoretically simple (no hadronic FSI). They are useful in study of color-singlet two-gluon system.

Many $J/\psi \rightarrow \gamma X$ ($X=\eta, \eta', \eta_c, f_2(1270), \ldots$) decay modes have been observed. A possible glueball state $f_J(2220)$ was reported by BES. Other candidates like $X(1860)$ were also observed.

Radiative decays $\Upsilon(1S) \rightarrow \gamma X$ are analogous to that of $J/\psi$. The decay branching fraction is scaled down by 1/25, due to the quark charges, masses and the total width of the quarkonia.

CLEO II observed $\Upsilon(1S) \rightarrow \gamma f_2(1270)$, consistent with scaling down factor. CLEO also set an upper limit on $f_J(2220)$ production.
\( \Upsilon(1S) \rightarrow \gamma h^+h^- \)

CLEO III

No significant structure at 2220 or 1860.
Confirm $f_2'(1270)$ in $\pi^+\pi^-$ mode and establish $J=2$ assignment.

$B(\Upsilon(1S) \to \gamma f_2'(1270)) = (10.2 \pm 0.8 \pm 0.7) \times 10^{-5}$

Observe $f_2'(1525)$ in $K^+K^-$ mode and establish $J=2$ assignment.

$B(\Upsilon(1S) \to \gamma f_2'(1525)) = (3.7^{+0.9}_{-0.7} \pm 0.8) \times 10^{-5}$

Set 90% CL upper limit on product branching fraction for $f_J(2220)$:

$B(\Upsilon(1S) \to \gamma f_J(2220)) \times B(f_J(2220) \to \pi^+\pi^-) < 8 \times 10^{-7}$,

$B(\Upsilon(1S) \to \gamma f_J(2220)) \times B(f_J(2220) \to K^+K^-) < 6 \times 10^{-7}$,

$B(\Upsilon(1S) \to \gamma f_J(2220)) \times B(f_J(2220) \to p\bar{p}) < 11 \times 10^{-7}$.

Set 90% CL upper limit on product branching fraction for $X(1860)$:

$B(\Upsilon(1S) \to \gamma X(1860)) \times B(X(1860) \to p\bar{p}) < 5 \times 10^{-7}$.
**\( \Upsilon(1S) \rightarrow \gamma h^0h^0 \)**

- Measured \( f_2(1270) \) production rate in \( \pi^0\pi^0 \) mode, consistent with \( \pi^+\pi^- \) mode.
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma f_2(1270)) = (10.5 \pm 1.6^{+1.9}_{-1.8}) \times 10^{-5}
  \]

- No resonance structure for \( f_0(1500) \) and \( f_0(1710) \) and 90% upper limits are set. The limits are order of magnitude lower than QCD factorization calculation (PRD66, 074015):
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma f_0(1500)) < 1.17 \times 10^{-5},
  \]
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma f_0(1710)) \times B (f_0(1710) \rightarrow \pi^0\pi^0) < 1.2 \times 10^{-6}.
  \]

- See two candidates in \( \eta\eta \) mode and no candidate in \( \pi^0\eta \) mode. UL are:
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma f_0(1500)) \times B (f_0(1500) \rightarrow \eta\eta) < 3.0 \times 10^{-6},
  \]
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma f_0(1710)) \times B (f_0(1710) \rightarrow \eta\eta) < 1.9 \times 10^{-6},
  \]
  
  \[
  B (\Upsilon(1S) \rightarrow \gamma\pi^0\eta) < 2.8 \times 10^{-6}.
  \]
Search for $\Upsilon(1S) \rightarrow \gamma \eta, \gamma \eta'$ (I)

- Production rates of $J/\psi \rightarrow \gamma \eta, \gamma \eta', \gamma f_2(1270)$ have been measured and
  \[ B(J/\psi \rightarrow \gamma \eta') / B(J/\psi \rightarrow \gamma f_2) \approx 3.4 \]
  \[ B(J/\psi \rightarrow \gamma \eta) / B(J/\psi \rightarrow \gamma f_2) \approx 0.7 \]

- $B(\Upsilon(1S) \rightarrow \gamma f_2(1270)) = 10.0 \times 10^{-5}$ by CLEO II and III.

- CLEO II set $B(\Upsilon(1S) \rightarrow \gamma \eta') < 1.6 \times 10^{-5}$ and
  \[ (\Upsilon(1S) \rightarrow \gamma \eta) < 2.1 \times 10^{-5}, \] corresponding to
  the ratio limits of 0.16 and 0.21 respectively.

- Several models (VDM, NRQCD, mixing with $\eta_b$) try to explain the lower rates and need to be tested.

- Decay modes: $\eta \rightarrow \gamma \gamma, \pi^+ \pi^- \pi^0, \pi^0 \pi^0 \pi^0$ are searched. No candidate seen.
Search for $\Upsilon(1S) \rightarrow \gamma \eta, \gamma \eta'$ (II)

$\eta' \rightarrow \pi^+\pi^-\eta$
$\eta \rightarrow \gamma\gamma$

CLEO III
Preliminary

No Signal

$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma \eta) < 9.3 \times 10^{-7}$,
$\mathcal{B}(\Upsilon(1S) \rightarrow \gamma \eta') < 1.77 \times 10^{-6}$

Strongly disfavors mixing with $\eta_b$.
Still consistent with VDM.
Barely consistent with NRQCD.
Search for $\Upsilon \rightarrow \gamma \mathcal{R}$, $\mathcal{R} \rightarrow (\geq 4 \ h^{\pm})$

Two body decay with a narrow resonance $\mathcal{R}$ results in monochromatic $\gamma$ in the lab frame.

A bump above the smooth background indicates a narrow resonance.

A series of fit at each $E_\gamma$ step to Chebyshyev polynomial function for background and Gaussian function for signal.

The production upper limit at each $E_\gamma$ is calculated from fit and map to $M_\mathcal{R}$.

Plot borrowed from PRD 74, 012003(2006)
Search for $\Upsilon \to \gamma R$, $R \to (\geq 4\ h^{\pm})$

**Upper Limit**

| $\Upsilon(1S)$ | $1.05 \times 10^{-3}$ | $1.82 \times 10^{-4}$ |
| $\Upsilon(2S)$ | $1.65 \times 10^{-3}$ | $1.69 \times 10^{-4}$ |
| $\Upsilon(3S)$ | $2.47 \times 10^{-3}$ | $3.00 \times 10^{-4}$ |

B.R upper limits are all $\sim 10^{-4}$.

No conflict with existing measurements.
Hadron productions in gluon rich and quark environment have been compared by many experiments.

At LEP 3 jet (q\bar{q}g) and 2 jet (q\bar{q}) events were used for comparison.

At CESR \( \Upsilon(1S) \rightarrow ggg \) and \( e^+e^- \rightarrow q\bar{q} \) were used. CLEO found that \( \phi, \Lambda \) and \( p \) production rates are higher in ggg decays.

Samples \( \Upsilon(1S) \rightarrow gg\gamma \) and \( e^+e^- \rightarrow q\bar{q}\gamma \) are better choices: Parton numbers are equal. Parton total energy can be equal.
Comparison Between $gg\gamma$ and $q\bar{q}\gamma$

Enhancement = \[ \frac{\text{Number of hadron per } gg\gamma \text{ event}}{\text{Number of hadron per } q\bar{q}\gamma \text{ event}} \]
Comparison Between $ggg$ and $q\bar{q}$

$$\text{Enhancement} = \frac{\text{Number of hadron per } ggg\text{ event}}{\text{Number of hadron per } q\bar{q}\text{ event}}$$
Integrated Enhancement Comparison

<table>
<thead>
<tr>
<th>1S</th>
<th>$gg\gamma$ vs. $qq\gamma$</th>
<th>$ggg$ vs. $qq$</th>
<th>1984 Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data $\Lambda$</td>
<td>$1.86 \pm 0.25 \pm 0.03$</td>
<td>$2.668 \pm 0.027 \pm 0.051$</td>
<td>$\sim 3 \pm 0.3$</td>
</tr>
<tr>
<td>MC</td>
<td>$1.381 \pm 0.039$</td>
<td>$1.440 \pm 0.003$</td>
<td></td>
</tr>
<tr>
<td>Data $p$</td>
<td>$1.21 \pm 0.11 \pm 0.03$</td>
<td>$1.623 \pm 0.014 \pm 0.088$</td>
<td>$\sim 1.5 \pm 0.3$</td>
</tr>
<tr>
<td>MC</td>
<td>$1.582 \pm 0.034$</td>
<td>$1.331 \pm 0.005$</td>
<td></td>
</tr>
<tr>
<td>Data $\bar{p}$</td>
<td>$1.45 \pm 0.14 \pm 0.21$</td>
<td>$1.634 \pm 0.014 \pm 0.081$</td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>$1.589 \pm 0.034$</td>
<td>$1.333 \pm 0.005$</td>
<td></td>
</tr>
<tr>
<td>Data $\phi$</td>
<td>$0.48 \pm 0.91 \pm 0.05$</td>
<td>$1.423 \pm 0.051 \pm 0.065$</td>
<td>$\sim 2 \pm 0.6$</td>
</tr>
<tr>
<td>MC</td>
<td>$0.702 \pm 0.027$</td>
<td>$0.836 \pm 0.003$</td>
<td></td>
</tr>
<tr>
<td>Data $f_2$</td>
<td>$1.34 \pm 0.84 \pm 0.05$</td>
<td>$0.658 \pm 0.029 \pm 0.065$</td>
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</tr>
</tbody>
</table>

- CLEO III measurement of $ggg$ vs $qq$ is consistent with CLEO II measurement.
- Enhancement effect is smaller in $gg\gamma$ vs $qq\gamma$.
- Enhancement is smaller for meson than baryon.
CLEO measured inclusive anti-deuteron and η′ in ϒ decays.

CLEO studied a group of radiative modes of ϒ decays.

CLEO III dedicated ϒ(1S), ϒ(2S), ϒ(3S) data samples have produced many interesting results.

They are rich laboratories to study hadronization process from gluon.