η_b Decays with charm final state

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Outline

η_b decays

Experiments about η_b and Our motivation

Heavy Quarkonium Spectroscopy from Data Book

- Charmonium

$$\underbrace{\eta_c(1^1S_0),\ J/\psi(1^3S_1)}_{\text{S-wave}},\ \underbrace{\chi_{c0}(1^3P_0), \chi_{c1}(1^3P_1), \chi_{c2}(1^3P_2)}_{\text{P-wave}},\ \ldots\ldots$$

- Bottomonium

$$\underbrace{\quad\quad,\ \Upsilon(1^3S_1)}_{\text{S-wave}},\ \underbrace{\chi_{b0}(1^3P_0), \chi_{b1}(1^3P_1), \chi_{b2}(1^3P_2)}_{\text{P-wave}},\ \ldots\ldots$$

- $^1S_0$ state η_b is still missing.

η_b mass: theoretical predictions

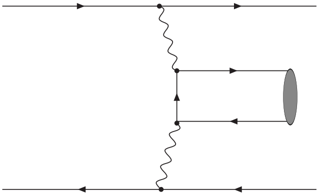
- Mass of η_b is important for its observation experimentally.
- Mass splitting $\Delta m = m(\Upsilon) - m(\eta_b)$:

Model	$\Delta m(MeV)$	Reference
lattice NRQCD	19-100	Heavy Quarkonium Physics Cern Yellow Book hep-ph/0412158
lattice potential	60-110	
pQCD	36-55	
1/m expansion	34-114	
potential model	57-141	

Table: Summary of mass splitting Δm.

Experiments: at LEP 2

- Three Collaborations: ALEPH, DELPHI, L3.
- Two-photon events: $\sigma \sim 0.3$pb and data $\sim 600\text{pb}^{-1}$



- With branching ratios to detected channels, there are only several events at most, theoretically.
- The upper limits for $\Gamma_{\gamma\gamma} Br(\eta_b \rightarrow \text{detected channel})$ were set.

Experiments: the LEP 2 search

Expt.	final states	$\Gamma_{\gamma\gamma} \times Br(keV)$	Reference
ALEPH	$\eta_b \to$4charged	<0.048	ALEPH Collaboration
	$\eta_b \to$6charged	<0.132	PLB**530**.56(2002)
L3	$K^+K^-\pi^0$	<2.83	L3 Collaboration
	4 charged	<0.21	Nucl.Phys.Proc.Suppl.
	6 charged	<0.33	**126**, 260, (2004)
	4 charged π^0	<0.50	
	6 charged π^0	<5.50	
	$\pi^+\pi^-\eta'$	<3.00	
DELPHI	4 charged	<0.093	DELPHI Collaboration
	6 charged	<0.270	PLB**634**.340(2005)
	8 charged	<0.780	

Table: Summary of data at LEP 2.

Experiments: the CLEO search

CLEO Collaboration, PRL.94.032001(2005), hep-ex/0207057

- set $\eta_b(1S)(\eta_b(2S))$ mass 35-110(20-45) MeV below $\Upsilon(1S)(\Upsilon(2S))$ mass .
- $\Upsilon(\mathrm{nS})$ radiative decays:
  $\Upsilon(3S) \to \gamma\eta_b(1S)$, $\Upsilon(3S) \to \gamma\eta_b(2S)$,$\Upsilon(2S) \to \gamma\eta_b(1S)$.
- photon with specific frequency as the signature.
- the upper limits of $Br(\Upsilon(nS) \to \gamma\eta_b(n'S))$ are set.

Experiments: the CLEO search

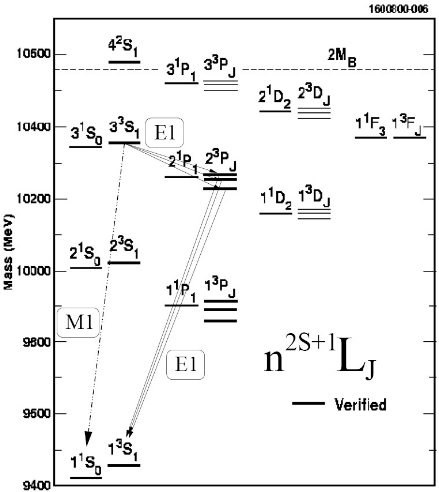


Figure: the Υ energy level spectrum and some E1 and M1 transitions. (from hep-ex/0207057)

Experiment: the CDF search

- Hadron collision at the Tevatron.
- η_b decay to double-J/ψ.

$$\eta \to J/\psi J/\psi \ \to \mu^+\mu^- + \mu^+\mu^- .$$

- Theoretical estimation for this channel by Braaten *et al.*, (Phys.Rev.D**63**,094006, (2001))

$$Br(\eta_b \to J/\psi J/\psi) \sim 7 \times 10^{-4\pm1}$$

Experiment: result of the CDF search

- "A small cluster of 7 events can be seen, where 1.8 events are expected from background."

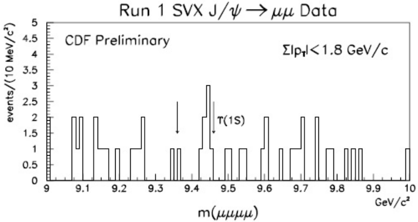


Figure 2. Mass distribution after selection. Arrows delimit the 100 MeV/c^2 search window, the upper side of which is set by the world-average $\Upsilon(1S)$ mass.

Figure: CDF' search.

(CDF Collaboration, J.Tseng FERMILAB-CONF-02-348-E)

- the mass of the cluster: $9445 \pm 6(stat)$MeV.

Experiment: the CDF search

Other estimations for $\eta_b \to J/\psi + J/\psi$

- Relativistic correction.

$$Br(\eta_b \to J/\psi J/\psi) = 2.4^{+4.2}_{-1.9} \times 10^{-8}$$

(Y.Jia, hep-ph/0611130)

- Radiative correction + Relativistic correction.

$$Br(\eta_b \to J/\psi J/\psi) = (2.1 - 18.6) \times 10^{-8}$$

(B.Gong, Y.Jia and J.X.Wang, PLB670,350(2009))

Other final states for observation of η_b

- Maltoni and Polosa's suggestion (PRD70.054014(2004))

$$\eta_b \to D^* \bar{D}^{(*)} + c.c.$$

- Their assumption: the $D^* \bar{D}^{(*)}$ channel might dominate the inclusive rate of η_b to charmed final states.

$$\Gamma(\eta_b \to D^* D^{(*)}) \leq \Gamma(\eta_b \to c\bar{c} + X).$$

- The branching ratio they evaluated

$$Br(\eta_b \to D^* D^{(*)}) \simeq 10^{-3} \sim 10^{-2}$$

η_b decays

η_b radiative charmonium decay

Our suggestion for hunting η_b

η_b's radiative decay:

$$\eta_b \to \gamma + J/\psi$$

The reasons:

- distinctive photons in final state;
- J/ψ is easy to detect, $Br(J/\psi) \to \mu^+\mu^-$ is about 6%;
- the branching ratio we have calculated.

Radiative decay: $\eta_b \to \gamma J/\psi$

- Leading-order calculation with the color-singlet model in the non-relativistic limit.
- NR limit:

$$p_q = p_{\bar{q}} = P_Q/2.$$

- Color-singlet model: all the non-perturbative effects can be taken into the wave function at the origin or matrix elements of color-singlet operators, which can be extracted from experiments, such as decays to lepton pair.

Radiative decay: $\eta_b \to \gamma J/\psi$

- For incoming η_b:

$$u(p_b)\,\overline{v}(p_{\bar b}) \quad \longrightarrow \quad \frac{1}{2\sqrt{2}}\,(\not{Q} + 2m_b)\, i\gamma_5 \times \left(\frac{1}{\sqrt{m_b}}\psi_{\eta_b}(0)\right) \otimes \left(\frac{\mathbf{1}_c}{\sqrt{N_c}}\right) .$$

- For outgoing J/ψ:

$$v(p_{\bar c})\,\overline{u}(p_c) \quad \longrightarrow \quad \frac{1}{2\sqrt{2}}\; \not{\epsilon}^*_{J/\psi}\,(\not{P} + 2m_c) \times \left(\frac{1}{\sqrt{m_c}}\psi_{J/\psi}(0)\right) \otimes \left(\frac{\mathbf{1}_c}{\sqrt{N_c}}\right) .$$

Radiative decay: $\eta_b \to \gamma J/\psi$

- Feynman diagrams:

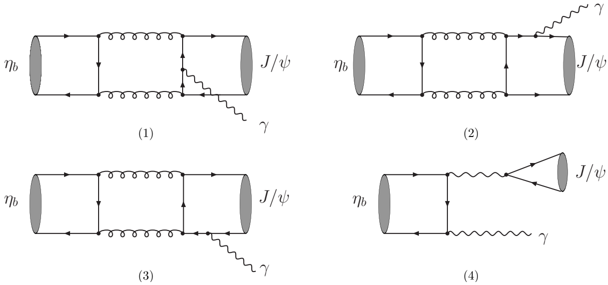


Figure: Both QCD and QED interactions are inclueded. The diagrams with crossed gluons are not drawn.

Analytical result: $\eta_b \to \gamma J/\psi$

Analytical result:

$$\mathrm{Br}[\eta_b \to J/\psi\gamma] = \frac{8\, e_c^2\, \alpha\, \alpha_s^2}{3\,\pi} \frac{m_c\, \psi_{J/\psi}^2(0)}{m_b^2\,(m_b^2 - m_c^2)} \left| f\left(\frac{m_c^2}{m_b^2}\right) - g\left(\frac{m_c^2}{m_b^2}\right) \right|^2 ,$$

where

$$\begin{aligned}
\mathrm{Re} f(u) &= \frac{2(1-u)}{2-u} \ln\left[\frac{u}{2(1-u)}\right] - \frac{2}{1+u} \left\{ \ln^2 2 + \frac{1}{2}\ln^2 u + \ln[2-u] \ln\left[\frac{u}{2(1-u)}\right] \right. \\
&+ \ln u \ln\left[\frac{2}{1-u}\right] - u \ln\left[\frac{u}{2-u}\right] \ln\left[\frac{u}{2(1-u)}\right] + 2\,\mathrm{Li}_2[-u] + \mathrm{Li}_2\left[\frac{u-1}{2u}\right] \\
&+ \left. 2\,\mathrm{Li}_2\left[\frac{u}{2}\right] - \mathrm{Li}_2\left[\frac{u^2-u}{2}\right] - u\,\mathrm{Li}_2\left[2 - \frac{2}{u}\right] \right\} , \\
\mathrm{Im} f(u) &= 2\pi \left\{ \frac{1-u}{2-u} + \frac{u \ln u}{1+u} - \ln[2-u] \right\} , \\
g(u) &= \frac{9\,\pi\, e_b^2\, \alpha}{2\,\alpha_s^2} \frac{1-u}{u} , \qquad\qquad \text{here } u = \frac{m_c^2}{m_b^2} .
\end{aligned}$$

Numerical result: $\eta_b \to \gamma J/\psi$

- QCD-initialed process and pure-QED process interfere destructively!
- It's necessary to include pure-QED contribution.

$$Br[\mathrm{QCD}] \sim \alpha\alpha_s^4 \quad , \qquad Br[\mathrm{QED}] \sim \alpha^3\,;$$
$$f = 3.5 - 2.4i \quad , \qquad g = 2.1\,.$$

- imaginary part of f dominates the decay amplitude.

Branching ratio:

$$Br[\eta_b \to \gamma J/\psi] = (1.5 \pm 0.8) \times 10^{-7}.$$

Consistent with the numerical result from (Y.J.Zhang et al, hep-ph/0701009).

Observation Possibility At the Tevatron

Theoretical production rate of η_b at the Tevatron (Maltoni and Polosa, PRD70,054014(2004).)

$$\sigma \sim 2.5\mu b.$$

Reconstruction of J/ψ experimentally: $J/\psi \to \ell^+ + \ell^-$

$$Br[J/\psi \to \mu^+\mu^-] \simeq Br[J/\psi \to e^+e^-] \simeq 6\%$$

With our estimation for $Br[\eta_b \to \gamma J/\psi]$

- Full Run 1 data : $100pb^{-1} \to$ 2 - 7 events.
- Future Run 2 data: $8.5fb^{-1}$.
  With efficiency for detecting leptons, 20 - 60 events.

Other radiative decays

- Replacing the flavor of quarks in initial or(and) final meson(s), we get the branching ratios for other decays:

$$Br[\eta_b \to \gamma\phi] = (0.3 - 6.9) \times 10^{-8}$$
$$Br[\eta_c \to \gamma\phi] = (2.1 - 8.6) \times 10^{-7}$$

- Since the NR approximation is NOT good for ϕ meson, these two branching ratios should be considered as very rough estimations.

(G.Hao, et al, JHEP02(2007)057)

η_b decays

η_b inclusive decay to J/ψ

Inclusive decay: $\eta_b \to J/\psi + X$

- Leading-order calculation in the non-relativistic limit.
- Feynman diagrams:

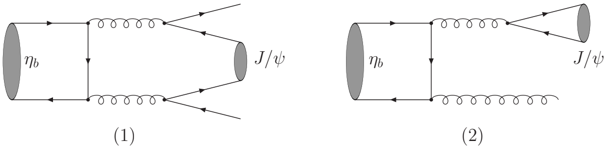


Figure: fig.1 and fig.2 is the contribution from color-singlet and color-octet respectively.

Color-Octet Mechanism

- A way to explain the production surplus of J/ψ and ψ'. (Braaten,*et al*, PRL74,(1995)3327)
- The $c\bar{c}$ pair formed a color-octet state at first, then it evolves to color-singlet meson through some soft processes. The probability is proportional to the matrix element of corresponding operator.
- This kind of process is v^{2n}-suppressed according to NRQCD. (Braaten,*et al*, PRD51,(1995)1125)

Numerical results: branching ratios

- If there is only contribution from color-singlet,

$$Br[\eta_b \to J/\psi + X] \sim 10^{-5}.$$

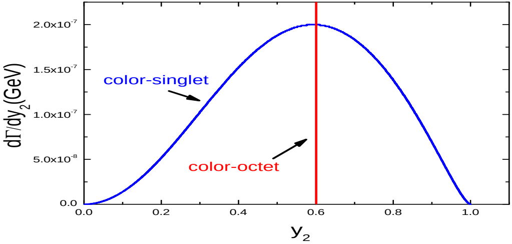
  If color-octet also contributes,

$$Br[\eta_b \to J/\psi + X] \sim 10^{-4}.$$

- numerical difference is obvious.

Numerical results: J/ψ distribution in final state

- In color-singlet process



- In color-octet process, J/ψ distribution is like an δ function.
- Also a distinctive difference.
- it's a chance to examine color-octet mechanism experimentally.

(G.Hao,C.F.Qiao and P.Sun, Phys.Rev.D76(2007)125013)

Summary

- The existence of the η_b is a solid prediction of the quark model. It's important and meaningful to suggest some final stats where η_b can be observed.
- We evaluate η_b radiative and inclusive decays to J/ψ. One might be the signal of η_b observation, and another might provide a channel to check color-octet mechanism.
- It's possible that these decays will be seen at the LHC or some future electronic colliders.

CLEO's recent evidence for η_b

CLEO Collaboration, Phys.Rev.D81:031104,2010
Radiative decay:

$$\Upsilon(3S) \to \gamma + \eta_b(1S)$$

Branching ratio:

$$Br(\Upsilon(3S) \to \gamma\eta_b) = (7.1 \pm 1.8 \pm 1.3) \times 10^{-4}$$

η_b mass:

$$M(\eta_b) = 9391.8 \pm 6.6 \pm 2.0\mathrm{MeV}$$

2010高能会议（南昌）

Thank you for your patience!

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