

# Upsilon Decays

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Bound upsilon states and their decays provide a unique laboratory for testing QCD, LQCD, and quarkonium potential models. I review recent results, some of which are significant improvements in precision over previous measurements and others are first-time observations. While most of the results presented are from CLEO III there are also notable contributions from BaBar and Belle who have just begun to exploit their strong capabilities for studying bound state upsilons.

## 1. Introduction

The physics to be extracted from properties and decays of bound state upsilons is rich. The masses and widths of the various states and cascade transitions between them test QCD, LQCD, and quarkonium potential models. Inclusive production of charmonium in upsilon decay tests QCD-inspired color-singlet and color-octet models. Radiative decays to light hadrons test scaling between charmonium and bottomium; they are also a source of glueballs should those exist. Searching for LFV decays, *e.g.*  $\Upsilon(1S) \rightarrow \tau\mu$ , probes physics beyond the SM.

After a long period of near stagnation, the study of bound state upsilons and their decays experienced an impressive renaissance, starting in 2001-02 with the CLEO III experiment collecting dedicated data samples at the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  resonances. The data collected correspond to  $21M$ ,  $10M$ , and  $5M$  resonance decays, respectively. In addition, BaBar and Belle have begun to analyze their wealth of data also with a view towards bound upsilon states, and have come out with exciting new results.

This report reviews highlights from the following subjects: (i) E1 photon transitions, (ii) “unusual” hadronic transitions, (iii)  $\Upsilon(1S)$  decay to charmonium, (iv) radiative decays of the  $\Upsilon(1S)$ , (v) precision measurements of  $B_{\mu\mu}$  and  $\Gamma_{ee}$ , and (vi) dipionic cascade transitions— an old topic on which CLEO III as well as BaBar and Belle have just shed new light.

## 2. E1 photon transitions

Photon transitions between bound upsilon states probe quarkonium potential models. In particular, measurement of transition energies and branching fractions probe the spin dependence and the magnitude of relativistic corrections. CLEO III has recently performed a definitive study[1] of the E1 transitions,  $\Upsilon(2S) \rightarrow \gamma\chi_b$ ,  $\Upsilon(3S) \rightarrow \gamma\chi_b$ , and  $\Upsilon(3S) \rightarrow \gamma\chi'_b$ . As one example of the sensitivity achieved, the branching fraction for the decay  $\Upsilon(3S) \rightarrow \gamma\chi_b$  ( $^1P_0$ ) was measured to be  $(0.30 \pm 0.04 \pm 0.10)\%$ . This allowed to discriminate between various theoretical models the predictions of which ranged between 0.006 and 0.74%.

Another highlight has been the discovery of the  $1^3D_J$  state[2], the first new upsilon state in 20 years and the first long-lived  $L = 2$  meson below open-flavor threshold. The mass difference between this  $1D$  state and the  $\Upsilon(1S)$  turned out to be one of ten “golden” experimental input quantities against which to test new, unquenched LQCD calculations[3]. This test has been spectacularly successful.

## 3. “Unusual” hadronic transitions

Hadronic cascade transitions between upsilon states test models of soft gluon emission with subsequent hadronization into light hadrons [8]. From the late 1970s until recently, the only observed such hadronic cascades had been dipion transitions between triplet S states. Now, results on two different types of hadronic cascades have been reported.

### 3.1. $\chi'_b \rightarrow \omega\Upsilon(1S)$

This is the first observation of a non-pionic cascade transition between  $b\bar{b}$  states, made by CLEO III via the channel,  $\Upsilon(3S) \rightarrow \gamma\chi'_b$ ,  $\chi'_b \rightarrow \omega\Upsilon(1S)$ , with  $\omega \rightarrow \pi^+\pi^-\pi^0$  and  $\Upsilon(1S) \rightarrow l^+l^-$ . The final state consists of  $\gamma + \pi^+\pi^-\pi^0 + l^+l^-$ . The invariant  $\pi^+\pi^-\pi^0$  mass distribution shows a clean  $\omega$  signal. The energy distribution of the photon associated with the  $\omega$  shows two peaks corresponding, respectively, to the  $J = 2$  and  $J = 1$  levels of  $\chi'_b$  (the cascade via the  $J = 0$  level is kinematically forbidden). CLEO III measures the branching fractions for  $\chi'_{bJ} \rightarrow \omega\Upsilon(1S)$  to be 1.6% and 1.1% for  $J = 1$  and  $J = 2$ , respectively[4]. Considering the tight available phase space these branching fractions are very large, in agreement with an early prediction by Gottfried[5]. A discussion of the spin dependence is given by Voloshin[6].

### 3.2. $\chi'_b \rightarrow \pi\pi\chi_b$

This is the first observation of a dipion cascade between non-S states, made by CLEO III via the cascade,  $\Upsilon(3S) \rightarrow \gamma\chi'_b$ ,  $\chi'_b \rightarrow \pi\pi\chi_b$ ,  $\chi_b \rightarrow \gamma\Upsilon(1S)$ ,

with  $\Upsilon(1S) \rightarrow l^+l^-$ . The final state consists of  $2\gamma + 2\pi + l^+l^-$ . The experimental challenge lies in the fact that the pions are very soft and that the main background process,  $\Upsilon(3S) \rightarrow \pi\pi\Upsilon(2S)$  with  $\Upsilon(2S) \rightarrow \gamma\chi_b$  where  $\chi_b \rightarrow \gamma\Upsilon(1S)$  as before, has identical final state particles with very similar kinematics. CLEO III applied two analysis methods, one in which both pions are detected (low statistics/low background) and one in which only one pion is detected and the other one is inferred from kinematic constraints (higher statistics/higher background). They observe the cascade transition as a  $6\sigma$  effect[7] and obtain the partial width,  $\Gamma_{\pi\pi}(\chi'_b) = (0.83 \pm 0.22 \pm 0.08 \pm 0.19) \text{ keV}$ , consistent with the prediction of  $\Gamma_{\pi\pi}(\chi'_b) \approx 0.4 \text{ keV}$  by Kuang & Yan [9].

#### 4. Inclusive decay to charmonium, $\Upsilon(1S) \rightarrow J/\psi X$

This decay tests models of charmonium production in gluon-rich environments, in particular the color-octet[11] and color-singlet[12] models, both of which predict a branching fraction and the shape of the inclusive  $J/\psi$  momentum distribution. CLEO III studied this process using their data sample of  $21M \Upsilon(1S)$  which is a nearly twentyfold increase in statistics over the only earlier measurement, by CLEO II, of more than a decade ago. CLEO III select events with inclusive high-momentum lepton pairs. They observe clean  $J/\psi$  signals in both the  $e^+e^-$  and the  $\mu^+\mu^-$  channel [13]. The measured branching fraction,  $B(\Upsilon(1S) \rightarrow J/\psi X) = (6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ , favors the color-octet model. The observed  $J/\psi$  momentum spectrum, however, is significantly softer than predicted by the color-octet model and also softer – although closer to – that predicted by the color-singlet model, indicating final state interactions not included in either model. Inclusive production of  $\psi(2S)$  and  $\chi_c$  in  $\Upsilon(1S)$  decay is also observed.

### 5. Radiative decays of $\Upsilon(1S)$

#### 5.1. $\Upsilon(1S) \rightarrow \gamma h^+ h^-$ , ( $h = \pi, K, p$ )

In this type of decay the light hadron pair is produced in a gluon-rich environment. It is an ideal source of glueballs should those exist. Scaling from the  $J/\psi$  where these decays have been studied extensively, to the  $\Upsilon(1S)$  the rates are expected to be suppressed by a factor of  $((q_b m_c)/(q_c m_b))^2 \approx 1/40$  and the branching fractions by a factor of  $\approx 1/25$ . CLEO III has studied these decays, as well as the  $\gamma\pi^0\pi^0$  final state which is free of  $\gamma\rho$  continuum background. They fit the observed structure in the  $hh$  invariant mass

distribution with relativistic, spin-dependent Breit-Wigner curves. The main results [14] are the following. (i) The  $f_2(1270)$  is confirmed in the  $\pi\pi$  channel, and from a fit within the helicity formalism the spin assignment,  $J = 2$ , is established. (ii) The  $f'_2(1525)$  is observed in the  $KK$  channel, also as  $J = 2$ . (iii) The rates are consistent with expectations based on scaling from the  $J/\psi$ . (iv) Tensor mesons dominate the observed structure. (v) No signal is found for  $f_J(2200)$  in any of the final states, leading to upper limits on the product branching fractions of the order of  $6 - 11 \times 10^{-7}$ .

#### 5.2. Search for $\Upsilon(1S) \rightarrow \gamma\eta(')$

These processes are theoretically simple in that there are no hadronic final-state interactions. They have been studied extensively in  $J/\psi$  radiative decay where good agreement with theory was found. Studying these decays in the epsilon system tests models of scaling such as VDM, NRQCD, and mixing with  $\eta_b$ . The previous upper limit (from CLEO II) on the branching fraction has stood at  $\approx 2 \times 10^{-5}$ . CLEO III chooses the 3 main decay modes for the  $\eta$  and 4 modes for the  $\eta'$  ( $3 \times (\eta\pi^+\pi^-)$  and  $\gamma\rho$ ). No signal is found in any of the channels in  $21M \Upsilon(1S)$  events, leading to upper limits,  $B(\Upsilon(1S) \rightarrow \gamma\eta) < 9.3 \times 10^{-7}$  and  $B(\Upsilon(1S) \rightarrow \gamma\eta') < 17.7 \times 10^{-7}$ . This strongly disfavors mixing with  $\eta_b$ . It is still consistent with VDM and, marginally, with NRQCD. These results are preliminary.

### 6. Precision measurement of $B_{\mu\mu}$ and $\Gamma_{ee}$

The muonic branching fraction and the di-electron width of a quarkonium resonance are fundamental quantities in themselves. Beyond that,  $B_{\mu\mu}$  frequently enters into derivation of other branching fractions while  $\Gamma_{ee}$  is important for comparisons with LQCD. CLEO III has re-measured  $B_{\mu\mu}$  and  $\Gamma_{ee}$  for the bound state epsilon resonances with high precision.

#### 6.1. $B_{\mu\mu}$ of $\Upsilon(1S)$ , $\Upsilon(2S)$ , and $\Upsilon(3S)$

Here, the main experimental challenges are precision luminosity measurement, subtraction of the copiously produced continuum muon pairs, and suppression of cosmic ray background. CLEO III reports[15] the new measurements,  $B_{\mu\mu}(\Upsilon(1S)) = (2.49 \pm 0.02 \pm 0.07)\%$ ,  $B_{\mu\mu}(\Upsilon(2S)) = (2.03 \pm 0.03 \pm 0.08)\%$ , and  $B_{\mu\mu}(\Upsilon(3S)) = (2.39 \pm 0.07 \pm 0.10)\%$ . This corresponds to a relative precision of 2–3% in each case, far exceeding that any previous measurement. Note also that while the value of  $B_{\mu\mu}$  for  $\Upsilon(1S)$  is consistent with previous measurements the results for  $\Upsilon(2S)$  and

$\Upsilon(3S)$  are significantly higher than the previous PDG values. This implies a downward shift in the values for the total widths of  $\Upsilon(2S)$  and  $\Upsilon(3S)$ .

## 6.2. $\Gamma_{ee}$ of $\Upsilon(1S)$ , $\Upsilon(2S)$ , and $\Upsilon(3S)$

The di-electron width,  $\Gamma_{ee}$ , of a bound upsilron state is proportional to the integral of the total cross section when scanning across the resonance in  $e^+e^-$  collisions. (The width cannot be “read off” directly because it is only of the order of  $keV$  whereas the observed resonance shape is dominated by the beam energy spread of typically several  $MeV$ .) The experimental challenge lies in tracking both the height of the resonance (luminosity measurement, efficiency, backgrounds) and its width (shift in beam energy). Effects contributing to the observed lineshape include continuum production of hadrons, two-photon fusion, cosmic-ray backgrounds, beam-gas background, and the radiative tails of lower mass resonances. CLEO III performed and analyzed repeated scans across each of  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  (11, 6, and 7, respectively, see figure 1). The final results are[16],  $\Gamma_{ee}(\Upsilon(1S)) = (1.354 \pm 0.005 \pm 0.020) keV$ ,  $\Gamma_{ee}(\Upsilon(2S)) = (0.619 \pm 0.007 \pm 0.009) keV$ , and  $\Gamma_{ee}(\Upsilon(3S)) = (0.446 \pm 0.004 \pm 0.007) keV$ . The results are consistent with and significantly more precise than any previous measurements. This allows a stringent test of LQCD where the quantities most reliably calculable are the ratios of di-electron widths. Figure 2 shows one such comparison between experiment and extrapolated LQCD calculations[17]. The agreement is good, and also presents a challenge to the LQCD community to further reduce the theoretical uncertainty.

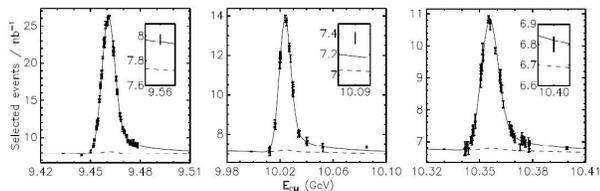


Figure 1: CLEO III scans of the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  resonances.

## 7. Dipion cascades between $\Upsilon(nS)$ states

In this paragraph,  $nS \rightarrow mS$  denotes dipion cascade transitions between triplet  $S$  states in bottomium,  $\Upsilon(nS) \rightarrow \pi\pi\Upsilon(mS)$ . Measurements of these cascades date back to the very early days of the LENA, Argus, Crystal Ball, CUSB, and CLEO I experiments. Quantities of interest are the branching fraction and,

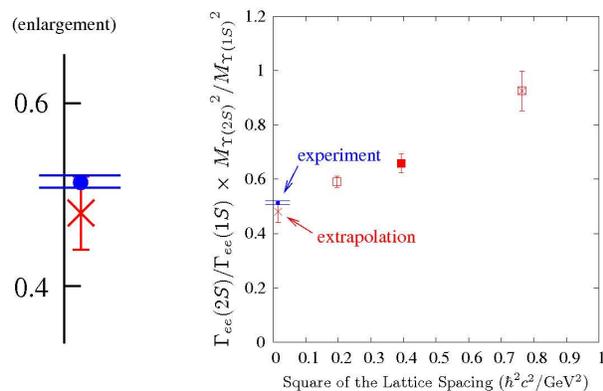


Figure 2: Comparison of LQCD calculations[17] with experimental results[16] on  $\Gamma_{ee}(\Upsilon(2S))/\Gamma_{ee}(\Upsilon(1S))$  from CLEO III. Shown on the left is a close-up of the region near zero lattice spacing.

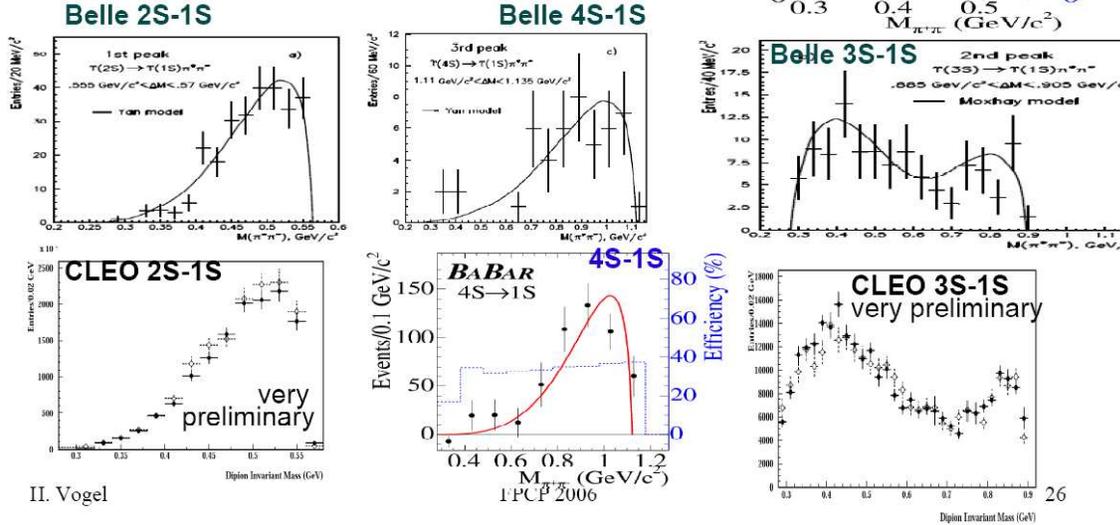
in particular, the distribution of the dipion invariant mass,  $M_{\pi\pi}$ . It has long been established that in the transition  $2S \rightarrow 1S$ ,  $M_{\pi\pi}$  peaks towards the upper end of the kinematic range just as in the corresponding transition in charmonium (conforming to the Yan model[8]). By contrast, in  $3S \rightarrow 1S$   $M_{\pi\pi}$  exhibits double peak structure suggestive of final-state interactions, intermediate resonance formation, and/or coupled-channel effects as in the Moxhay model[10]). After nearly two decades of stagnation this subject has recently found renewed interest with experimental input from CLEO III as well as from BaBar and Belle. CLEO III is in the process of finalizing a high-statistics study of the  $2S \rightarrow 1S$ ,  $3S \rightarrow 1S$ , and  $3S \rightarrow 2S$  cascades. Babar just reported[18] results on  $4S \rightarrow 1S$  and  $4S \rightarrow 2S$  cascades. Belle also reported[19] results on  $4S \rightarrow 1S$  and, from their ISR data sample results on  $3S \rightarrow 1S$  and  $2S \rightarrow 1S$ . The picture emerging from these results is intriguing, as shown in figure 3. Evidently,  $\Delta n = 2$  transitions exhibit double peak structure whereas  $\Delta n \neq 2$  transitions do not. At present there does not appear to be a theoretical explanation for such pattern.

## 8. Summary

The study of properties and decays of bound upsilron states has recently gained renewed interest. On the experimental side, results from CLEO III have been either first time observations or re-measurements which set new standards of precision. In addition, BaBar and Belle have begun to exploit the wealth of bound state upsilron data produced as “byproduct” of running on the  $\Upsilon(4S)$ , and have already weighed in with exciting new results on dipion cascade transitions. Furthermore, Belle has done dedicated running at the  $\Upsilon(3S)$  and may do some more in the near future. The results provide key inputs to theory includ-

## Dipion Cascades: Hot News or What's So Special About $\Delta n=2$ ?

Belle: hep-ex/0512034  
BaBar: talk at QCD Moriond'06  
CLEO: very preliminary



II. Vogel

Figure 3: Compilation of various recently measured  $M_{\pi\pi}$  distributions of dipion cascade transitions between triplet S states in the upsilon system. The data are from Babar, Belle, and CLEO III.

ing quarkonium potential models, QCD and, in particular, to LQCD where calculations are approaching the few percent level in precision.

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