HEAVY QUARKONIA

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ABSTRACT

Recent experimental results on heavy quarkonia spectroscopy and decays are reviewed. In particular, new results are discussed on charmonium spin singlet states, bottomonium D-states, photon and hadronic transitions from heavy quarkonium states, and the unexplained narrow X(3872) state.

1 Introduction

Heavy quarkonia are the bound states of charm and bottom quarks. They are strong interaction analogs of positronium. Because charm and bottom quarks have large masses (~1.5 and ~4.5 GeV), velocities of quarks in hadrons are nonrelativistic. The strong coupling constant α_s is small (~0.3 for $c\bar{c}$ and ~0.2 for $b\bar{b}$). Therefore heavy quarkonia spectroscopy is a good testing ground for theories of strong interactions: QCD in both perturbative and non-perturbative

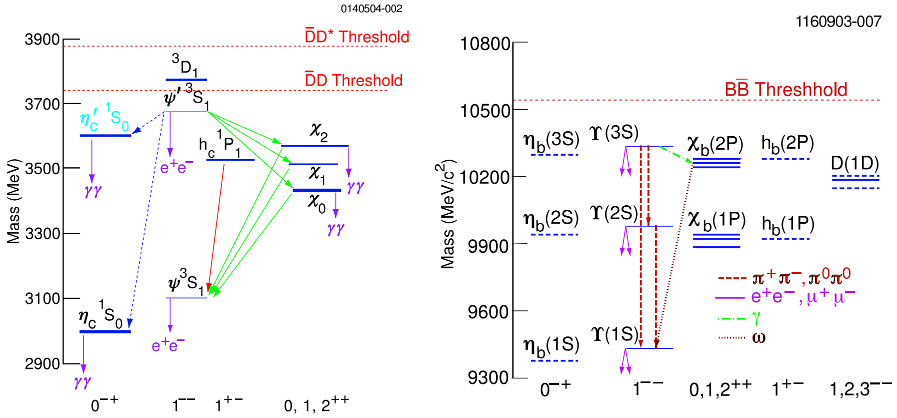

Figure 1: *The spectra for charmonia (left) and bottomonia (right) below and near the open flavor threshold. Some typical transitions are indicated. None of the singlet η_b or h_b bottomonium states or h_c charmonium state have been observed yet.*

regimes, QCD inspired purely phenomenological potential models, NRQCD and Lattice QCD.

Quarkonium states can be produced (fig.1) in $e^+e^- \to \gamma^* \to q\bar{q}$ processes (direct production of n^3S_1: $J^{PC} = 1^{--}$ vector states), two photon fusion processes at the e^+e^- colliders (production of η_c, η_c', $\chi_{0,2}$: $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$ states), $p\bar{p}$ annihilation via two or three gluons (production of $q\bar{q}$ mesons with any quantum numbers), B meson decays (production of states with any quantum numbers with associated particles), radiative or hadronic transitions from higher states of quarkonia.

2 New in Charmonium Spectroscopy

In this section new experimental results on charmonium states produced below the open flavor production threshold are reviewed, obtained from the large data samples collected with the BaBar, Belle, BES and CLEO detectors.

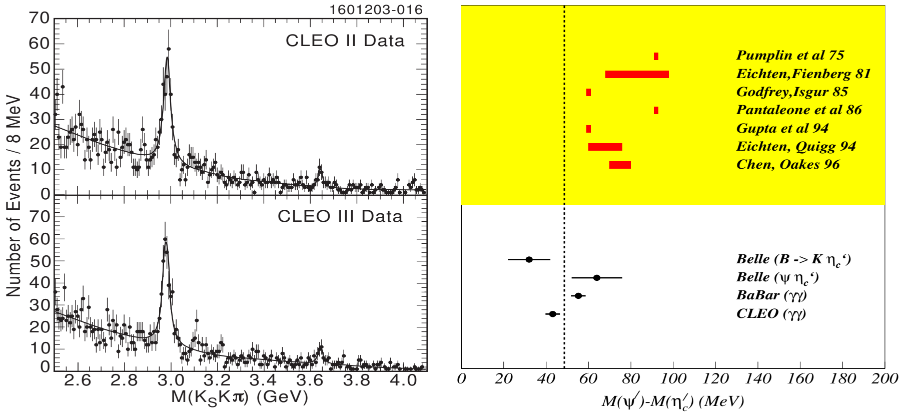

Figure 2: $K_sK^{\pm}\pi^{\mp}$ *invariant mass distributions for events in two photon fusion processes from the CLEO data, indicating* η_c *and* η_c' *resonances (left). A summary of the theoretical predictions and new experimental measurements of* $\Delta M_{hf}(2S)$ *(right).*

2.1 Spin Singlet States

These states are generally the most difficult states to access and study because they are not directly formed in e^+e^- annihilation and the radiative decays of spin triplet states $^3S_1(J/\psi,\ \psi',\ \Upsilon,\ ...)$ to spin singlet states $^1S_0(\eta_c, \eta_b)$ are M1 transitions and therefore are highly suppressed. In $^1P_1(h_c, h_b)$ cases, the radiative decays are entirely forbidden by C-conservation. As a result, no singlet states have ever been identified in bottomonium and only the η_c singlet state was identified in charmonium until recently.

The radial excitation of the charmonium spin singlet ground state, $\eta_c'(2^1S_0)$, is known to be bound. It is important to identify it because it can shed light on the nature of the spin-spin hyperfine interaction between a quark and antiquark. The hyperfine interaction produces the splitting between the spin-singlet and spin-triplet states. For the charmonium $1S$ states splitting $(M(J/\psi) - M(\eta_c))$ is known to be $\Delta M_{hf}(1S) = 117 \pm 2$ MeV [1]. It is important to know hyperfine splitting for the $2S$ states, because these states increasingly sample the confinement part of the $q\bar{q}$ potential.

Crystal Ball has claimed observation of η_c' in an earlier measurement with $M(\eta_c') = 3594 \pm 5$ MeV in the ψ' inclusive photon spectrum [2]. CLEO, with similar sensitivity, does not confirm the Crystal Ball observation [3]. In 2002 Belle announced the evidence for η_c' in two different measurements: in $B \to (\eta_c')K \to (K_s K^{\pm}\pi^{\mp})K$ channel with $M(\eta_c') = 3654 \pm 6 \pm 8$ MeV [4] and in double charmonium production $e^+e^- \to J/\psi\eta_c'$ with $M(\eta_c') = 3622 \pm 12$ MeV [5]. This was followed by CLEO [6] (fig.2) and BaBar [7] observations of η_c' in two-photon fusion processes with the results:

CLEO	BaBar
$M(\eta_c') = 3642.9 \pm 3.1 \pm 1.5$ (MeV),	$M(\eta_c') = 3630.8 \pm 3.4 \pm 1.0$ (MeV),
$\Gamma(\eta_c') < 31$ MeV (90% CL),	$\Gamma(\eta_c') = 17.0 \pm 8.3 \pm 2.5$ (MeV).
$\Gamma_{\gamma\gamma}(\eta_c') = 1.3 \pm 0.6$ (keV)[1].	

The world average of the η_c' mass value (fig.2) is $M(\eta_c') = 3637.4 \pm 4.4$ (MeV) and corresponds to hyperfine mass splitting $\Delta M_{hf}(2S) = M(\psi') - M(\eta_c') = 48.6 \pm 4.4$ (MeV). This is a factor 2.4 smaller than $\Delta M_{hf}(1S)$ and is not predicted by the potential model calculations (fig.2). This result should lead to a new insight into coupled channel effects and the spin-spin contribution of the confinement part of $q\bar{q}$ potential.

2.2 Two Body Hadronic $\psi(2S)$ Decays

According to pQCD, because both ${}^3S_1 \to \gamma \to e^+e^-$ and ${}^3S_1 \to ggg \to$ *hadrons* decays are proportional to $|\psi(0)|^2$, the ratio

$$Q_h \approx \frac{\mathcal{B}(\psi(2S) \to h)}{\mathcal{B}(J/\psi \to h)} \approx \frac{\mathcal{B}(\psi(2S) \to e^+e^-)}{\mathcal{B}(J/\psi \to e^+e^-)} \approx (13 \pm 1)\%. \tag{1}$$

It was noted many years ago that the vector-pseudoscalar (VP) decay to $\rho\pi$ strongly violates the expectation of equation 1. This problem is known as the "$\rho - \pi$" puzzle and has received great theoretical attention. BES has recently measured vector-tensor (VT) (ωf_2, ρa_2, $K^*\bar{K}_2^*$, $\phi f_2'$) decays of ψ' with a data sample of 14×10^6 ψ' events [8]. CLEO has measured ψ' decays to VP final states ($\rho\pi$, $\omega\pi$, $\rho\eta$, $K^{*0}\bar{K}^0$) and to $\pi^+\pi^-\pi^0$ with a data sample of 3×10^6 ψ' events. [9]. The results are summarized in fig.3.

The experimental status of the "$\rho - \pi$" puzzle, based on the new measurements, can be summarized as follows:

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[1] Assuming that the branching fractions for η_c and η_c' decays to $K_sK\pi$ are equal and using $\Gamma_{\gamma\gamma}(\eta_c) = 7.4 \pm 0.4 \pm 0.5 \pm 2.3(br)$ (keV) [6].

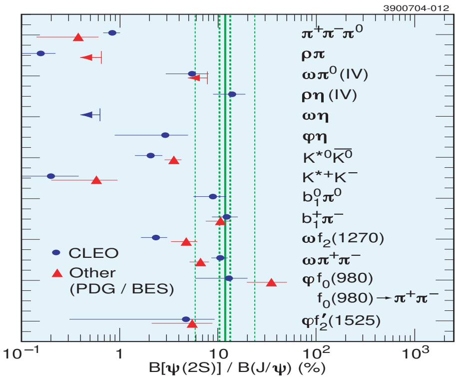

Figure 3: *The ratio of branching fractions of ψ' and J/ψ decays to different final hadronic states. Vertical solid line indicates the pQCD expectation.*

- For VP final states, decays through three gluons are severely suppressed with respect to the 13% rule and the corresponding isospin violating channels ($\omega\pi$, $\rho\eta$) are not;
- VT decay modes are suppressed by a factor of 3-5 compared to the 13% rule;
- Axial-pseudoscalar decay modes do not appear to be suppressed.

2.3 Radiative Transitions from $\psi(2S)$

The measurements of radiative E1 electric dipole transitions ($\Delta L = 1$, $\Delta S = 0$) from $\psi(2S)$ were mainly done in 1980s by the Crystal Ball [10]. The latest improvements of these transition measurements come from CLEO with a $\psi(2S)$ data sample comparable to the Crystal Ball sample. The preliminary CLEO results from the $\psi(2S)$ inclusive photon spectrum are [3]: $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ}) = [9.75 \pm 0.14 \pm 1.17, 9.64 \pm 0.11 \pm 0.69, 9.83 \pm 0.13 \pm 0.87]\%$ for $J = [2,1,0]$, respectively and for the "hindered" M1 transition: $\mathcal{B}(\psi(2S) \to \gamma\eta_c) = (0.278 \pm 0.033 \pm 0.049)\%$.

BES has measured the following branching fractions, using $\gamma\gamma J/\psi$ events, from a sample of 14×10^6 $\psi(2S)$ decays: $\mathcal{B}(\psi(2S) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi) = (2.81 \pm 0.05 \pm 0.23)\%$, $\mathcal{B}(\psi(2S) \to \gamma\chi_{c2} \to \gamma\gamma J/\psi) = (1.62 \pm 0.04 \pm 0.12)\%$, $\mathcal{B}(\psi(2S) \to \pi^0 J/\psi) = (1.43 \pm 0.14 \pm 0.12) \times 10^{-3}$, $\mathcal{B}(\psi(2S) \to \eta J/\psi) = (2.98 \pm 0.09 \pm 0.23)\%$ [11]. A two photon cascade measurements from the CLEO data should be forthcoming soon.

3 New in Upsilon Spectroscopy

In this section new results are reviewed from the large data samples collected with the CLEO detector running at and in the vicinity of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances (about 20, 10 and 5 million events, respectively).

3.1 First Observation of a $\Upsilon(1D)$ State

D-wave states in charmonium are expected to be unbound and none, except the vector state at 3770 MeV, have ever been firmly identified. In bottomonium the $1D$ and $2D$ states are all expected to be bound but, until now, none had been identified. The 1^3D_2 state has been identified with a significance of 10.2σ at CLEO in the four photon cascade (fig.1) [12]: $\Upsilon(3S) \to \gamma\chi_b(2P)$, $\chi_b(2P) \to \gamma\Upsilon(1D)$, $\Upsilon(1D) \to \gamma\chi_b(1P)$, $\chi_b(1P) \to \gamma\Upsilon(1S)$, followed by the $\Upsilon(1S)$ annihilation into e^+e^- or $\mu^+\mu^-$. The measured mass $M(1^3D_2) = 10161.1 \pm 0.6 \pm 1.6$ (MeV) is in agreement with both lattice and potential model calculations. The measured product branching ratio of the five decays is $(2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$ and is also in agreement with theoretical estimates.

3.2 $\mathcal{B}_{\mu\mu}$ of the Υ States

The total width (Γ) of the narrow $\Upsilon(1S, 2S, 3S)$ resonances produced in e^+e^- interactions can not be measured directly because their natural width (25-50 keV) is much smaller than the energy resolution of an e^+e^- collider (4-5 MeV). An indirect method of determining $\Gamma(\Upsilon(nS))$ is to combine the leptonic branching fraction ($\mathcal{B}_{ll}$) with the leptonic decay width (Γ_{ll}), i.e., $\Gamma = \Gamma_{ll}/\mathcal{B}_{ll}$. Assuming lepton universality, Γ_{ll} can be replaced with Γ_{ee} (CLEO plans to measure Γ_{ee} with a few percent precision from scans of the resonant line shapes) and $\mathcal{B}_{ll}$ replaced with $\mathcal{B}_{\mu\mu}$. Therefore the precise measurement of $\mathcal{B}_{\mu\mu}$ leads to a precise determination of $\Gamma(\Upsilon(nS))$.

CLEO has measured $\mathcal{B}_{\mu\mu}$ for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances by comparing muon and hadron yields at the peaks of resonances and the preliminary results are: $\mathcal{B}_{\mu\mu}(\Upsilon(1S)) = (2.53 \pm 0.02 \pm 0.05)\%$, $\mathcal{B}_{\mu\mu}(\Upsilon(2S)) = (2.11 \pm 0.03 \pm 0.05)\%$ and $\mathcal{B}_{\mu\mu}(\Upsilon(3S)) = (2.44 \pm 0.07 \pm 0.05)\%$. The $\Upsilon(1S)$ result agrees with the PDG average [1] but the $\Upsilon(2S, 3S)$ results are significantly higher. They also imply narrower $\Gamma(\Upsilon(2S, 3S))$. Results are shown in fig.4.

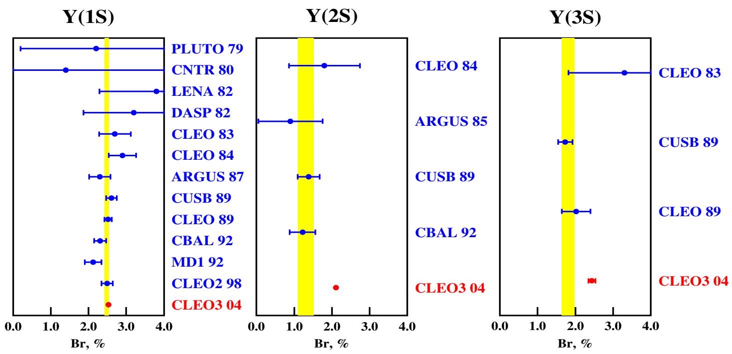

Figure 4: *Comparison of the new preliminary CLEO results of* $\mathcal{B}(\Upsilon \to \mu^+\mu^-)$ *to other available measurements and the PDG average.*

3.3 $\Upsilon(1S)$ Decays to Charmonium Final States

An explanation for the unexpected large charmonium production rates in $p\bar{p}$ collisions at the Tevatron was given by *color octet* models, where a single gluon fragments into a color octet ${}^3S_1$ $c\bar{c}$ pair which then evolves non-perturbatively into a color-singlet by emission of a soft gluon. *Color singlet* models produce final state $c\bar{c}$ mesons with two gluons. $\Upsilon(1S)$ decays are a good testing ground for the color octet and color singlet model predictions.

CLEO has measured [13] the branching ratio $\mathcal{B}(\Upsilon(1S) \to J/\psi + X) = (6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ using $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ decays. Feed-down to J/ψ from other charmonium states, e.g., ψ', χ_{cJ}, is included. The color octet [14] and color singlet [15] model predictions of the branching fraction (6.2×10^{-4} and 5.9×10^{-4}, respectively) are both in agreement with the above result. However, the continuum subtracted J/ψ momentum spectrum (fig.5) is in contradiction with the present color octet model prediction.

3.4 Neutral Dipion Transitions of $\Upsilon(3S)$ to $\Upsilon(1S)$ and $\Upsilon(2S)$

Precise measurements of the dipion transition branching ratios for $\Upsilon(3S) \to \Upsilon(2S, 1S)$ and dipion invariant mass spectra provide an experimental testing ground for many theoretical calculations [16], isospin conservation validation in charged and neutral dipion transition modes, and the deviation of dipion invariant mass from the phase space description.

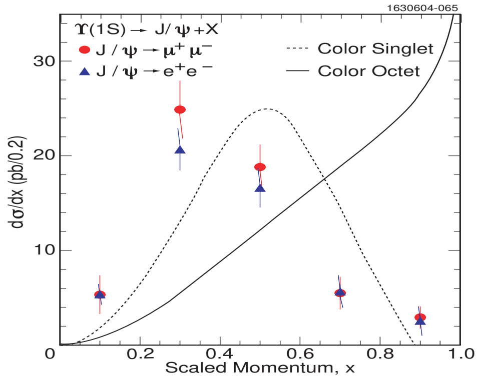

Figure 5: *J/ψ momentum spectrum in $\Upsilon(1S) \to J/\psi X$ from the CLEO data. Theoretical expectations based on the color-octet and color-singlet models are shown with lines.*

CLEO has measured the following preliminary branching ratios:

$$\mathcal{B}(\Upsilon(3S) \to \pi^0\pi^0\Upsilon(2S)) = 2.02 \pm 0.18 \pm 0.38\ (\%),$$
$$\mathcal{B}(\Upsilon(3S) \to \pi^0\pi^0\Upsilon(1S)) = 1.88 \pm 0.08 \pm 0.31\ (\%).$$

The $\pi^0\pi^0$ effective mass spectrum from $\Upsilon(3S) \to \pi^0\pi^0\Upsilon(2S)$ has the shape consistent with several theoretical predictions. $\Upsilon(3S) \to \pi^0\pi^0\Upsilon(1S)$ was found to have a double peaked shape, also observed in the charged pion transitions [16].

4 New Narrow State $X(3872)$

Belle recently observed a narrow state, $X(3872)$, in $B^\pm \to K^\pm X$, $X \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$, measuring $M(X) = 3872.0 \pm 0.6 \pm 0.5$ (MeV) and $\Gamma < 2.3$ MeV (90% CL) [17]. CDF [18] and D0 [19] in $p\bar{p} \to X(3872) + ...$, $X \to \pi^+\pi^- J/\psi$ and BaBar [20], in the same channel as Belle, confirmed this observation with $M(X) = [3871.3 \pm 0.7 \pm 0.4, 3871.8 \pm 3.1 \pm 3.0, 3873.4 \pm 1.4]$ MeV, respectively.

Many theoretical papers exist interpreting the $X(3872)$ state as: - a conventional charmonium state; - a $D\bar{D}^*$ molecule; - an exotic state. Identification of the quantum numbers is important to understand the structure of the state.

CLEO has searched for $X(3872)$ with $\sim$15 fb^{-1} of CLEO III data in untagged $\gamma\gamma$ fusion production, where the state can be produced if it has $J^{PC} = 0^{\pm+}, 2^{\pm+}, ...$, and initial state radiation (ISR) production, where the state can

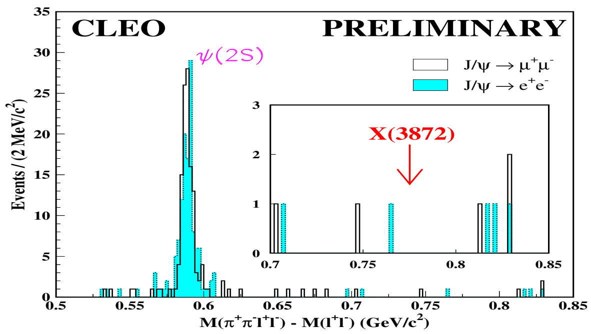

Figure 6: *Observed distribution of counts as a function of the effective mass difference* $M(\pi^+\pi^-l^+l^-) - M(l^+l^-)$ *from the CLEO data. The arrow indicates expected location of the* $X(3872)$ *signal.*

be produced if it has $J^{PC} = 1^{--}$. The exclusive channels $X \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ were analyzed. No signals were found and the following preliminary upper limits were set (fig.6):

$$(2J+1)\Gamma_{\gamma\gamma}\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 16.7 \text{ eV (90\% CL) in } \gamma\gamma \text{ fusion},$$
$$\Gamma_{ee}\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 6.8 \text{ eV (90\% CL) in ISR}.$$

Systematic errors are included in the upper limits.

5 Summary

Heavy quarkonium physics is an active field. Large data samples are being collected and analyzed for quarkonia in e^+e^- annihilation by BES-II ($c\bar{c}$), CLEO III ($b\bar{b}$), CLEOc ($c\bar{c}$).

Many new important experimental observations and measurements are available and many others are expected.

Progress is being made in NRQCD and Lattice QCD calculations. Hopefully many unresolved puzzles will be resolved soon.

6 Acknowledgements

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