Hadron Spectroscopy at CLEO

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Abstract. New measurements of the masses and decay branching fractions of charmonium and bottomonium states using the data collected by the CLEO detector are presented. These include CLEO identification of the singlet states $\eta'_c(2S)$, $h_c(1P)$, and $\eta_b(1S)$. Comparison with other experimental measurements and theoretical models is also presented.

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INTRODUCTION

The QCD interaction can be studied in light quark ($u, d, s$) hadrons as well as heavy quark ($c, b$) hadrons. In contrast to light quarks, heavy quark states are narrow and do not mix with the states of other quarks. This is illustrated in Fig. 1 (left) for charmonium. Also, the effective coupling constant and relativistic problems are far more tractable. Thus, the spectra of charmonium and bottomonium are easier to characterize and study.

CLEO DATA FOR CHARMONIUM AND BOTTOMONIUM SPECTROSCOPY

The world’s largest pre–BESIII sample of 26 million $\psi(2S)$ comes from CLEO. These $\psi(2S)$ data have been used to study the spectroscopy of $\chi_c J(3P_J)$ and $h_c(1P_1)$. Using $\pi\pi$ tag in the decay $\psi(2S) \to \pi^+\pi^- J/\psi (B=35\%)$, the spectroscopy of $J/\psi$ is also studied.

CLEO collected a sample of 21 million $\Upsilon(1S)$, 9 million $\Upsilon(2S)$, and 6 million $\Upsilon(3S)$. Besides bottomonium spectroscopy, the $\Upsilon$ data are used for charmonium spectroscopy using two-photon fusion reactions.

My talk contains two parts: (a) CLEO measurements of the masses of charmonium and bottomonium singlet states $\eta'_c(2S)$, $h_c(1P)$, and $\eta_b(1S)$, and their implications for the $q\bar{q}$ hyperfine interaction; (b) CLEO measurements for the decay branching fractions of charmonium and bottomonium states.

THE $q\bar{q}$ HYPERFINE INTERACTION

In the quark model the hyperfine spin–spin interaction determines the ground-state masses of the hadrons. The mass of a pseudoscalar or vector $q\bar{q}$ meson is

$$M(q_1\bar{q}_2) = m_1(q_1) + m_2(q_2) + A \left[ \frac{s^*_1 \cdot s^*_2}{m_1 m_2} \right].$$

The $s^*_1 \cdot s^*_2$ spin–spin, or hyperfine interaction gives rise to the hyperfine, or spin-singlet/spin-triplet splitting in quarkonium spectrum,

$$\Delta M_{hf}(nL) = M(n^3L_J) - M(n^3L_{J-1}).$$

The hyperfine interaction is not well understood because until recently there were not enough experimental data to provide the required constraints for the theory. For thirty years after the discovery of $J/\psi$, the only hyperfine splitting measured in a hidden flavor meson was $\Delta M_{hf}(1S) = 116.4 \pm 1.2$ MeV [1]. No other singlet states, $\eta'_c(21S_0)_{c\bar{c}}$, $h_c(1^1P_1)_{c\bar{c}}$, or $\eta_b(1^1S_0)_{b\bar{b}}$ were identified, and none of the important questions about the hyperfine interaction could be answered. This has changed in the last few years.
**FIGURE 1.** (left) Spectra of the states of Charmonium. (right) Schematic of the QCD $q\bar{q}$ potential (solid line), and its Coulombic and confinement parts (dotted lines). The vertical lines show the approximate location of the $|c\bar{c}\rangle$ charmonium and $|b\bar{b}\rangle$ bottomonium bound states.

**FIGURE 2.** The invariant mass $M(K_S K\pi)$ spectra from two–photon fusion measurements by CLEO (left) and BaBar (right). The $\eta'(2S)$ peak is prominent in both spectra.

$\eta_c'(2S)$, Hyperfine Splitting in a Radial Excitation

In 2002, Belle claimed identification of $\eta_c'$ in the decay of 45 million $B$ mesons, $B \rightarrow K(S) K\pi$ and reported $M(\eta_c') = 3654 \pm 10$ MeV, which would correspond to $\Delta M_h(2S) = 32 \pm 10$ MeV [2], a factor two smaller than expected and a factor four smaller than $\Delta M_h(1S)$. It became important to confirm this result.

There are two important ways $2S$ states differ from $1S$ states. $1S$ states, with $r \approx 0.4 f$, lie in the Coulombic region ($\sim 1/r$) of the $q\bar{q}$ potential, $V = A/r + Br$, whereas the $2S$ states, with $r \approx 0.8 f$, lie in the confinement part ($\sim r$) of the potential (see Fig. 1, right). The spin–spin potential in the two regions could be different. The second difference is that the $2S$ states, particularly $\psi(2S)$, lie close to the $D\bar{D}$ breakup threshold at 3730 MeV, and can be expected to mix with the continuum as well as higher $1^{--}$ states. All in all, it is important to nail down $\eta_c'$ experimentally, and measure its mass accurately.

This was successfully done by CLEO [3] and BaBar [4] in 2004 by observing $\eta_c'$ in two–photon fusion, $\gamma\gamma \rightarrow \eta_c' \rightarrow K_S K\pi$. The two observations are shown in Fig. 2. The average of all measurements is $M(\eta_c') = 3637 \pm 4$ MeV [1], which leads to $\Delta M_h(2S) = 49 \pm 4$ MeV, which is almost a factor 2.5 smaller than $\Delta M_h(1S)$. Explaining this large difference is a challenge to the theory. The challenge for the experimentalists lies in completing the spectroscopy of $\eta_c'$, now that its mass is known. In particular, it is important to measure its width.
\[
\begin{align*}
\Psi'(3686) & \xrightarrow{\gamma(E1)} 1^{--} \\
\pi^0 & \xrightarrow{1^{--}} \gamma(E1) \\
\chi_c(3P) & \xrightarrow{2^{++}} 1^{++} \\
3525 & \xrightarrow{0^{++}} \chi_c(3P) \\
h_c(1^1P_1) & \xrightarrow{\eta_c} \gamma h_c.
\end{align*}
\]

**FIGURE 3.** Comparing allowed E1 transitions from \(\psi'(3S_1)\) to \(\chi_c(3P_J)\) states of charmonium with the isospin forbidden \(\pi^0\) transition to the singlet P–state \(h_c(1^P_1)\).

\[
h_c(1^1P_1), \text{ Hyperfine Interaction in } P\text{-wave}
\]

In this case, we have a very simple, and provocative theoretical expectation, namely

\[
\Delta M_{hf}(1P) \equiv M(3P) - M(1P) = 0.
\]  \tag{1}

This arises from the fact that a non-relativistic reduction of the Bethe-Salpeter equation makes the hyperfine interaction a contact interaction. Since only S–wave states have finite wave function at the origin,

\[
\Delta M_{hf}(L \neq 0) = 0.
\]  \tag{2}

We can test this prediction in charmonium by

- identifying the singlet–P state \(h_c(1^1P_1)\), and
- by estimating \(M(3P)\), given the masses of the triplet–P states \(\chi_{0,1,2}(3P_{0,1,2})\).

The experimental identification of \(h_c(1^1P_1)\) is even more difficult than that of \(\eta_c\). The centroid of the \(3P_J\) states is at \(3525.30 \pm 0.04\) MeV \([1]\). If Eq. 1 is true, \(M(h_c) \approx 3525\) MeV, i.e., \(\sim 160\) MeV below the \(\psi(2S)\) state from which it must be fed. Unfortunately, populating \(h_c\) has several problems.

- The radiative transition \(\psi(2S)(1^{--}) \rightarrow \gamma h_c(1^{++})\) is forbidden by charge conjugation invariance.
- The only other alternative is to populate \(h_c\) in the reaction \(\psi(2S) \rightarrow \pi^0 h_c\). But that is not easy, because a \(\pi^0\) transition \((M(\pi^0) = 139\) MeV) has very little phase space, and further, the reaction is forbidden by isospin conservation. Nevertheless, this is the only possible way of populating \(h_c\), and we at CLEO had to valiantly go for it. An illustration of the allowed E1 transitions from \(\psi(2S)(3S_1)\) to \(\chi_c(3P_J)\) states and the isospin forbidden \(\pi^0\) transition to the singlet P–state \(h_c(1^P_1)\) is shown in Fig. 3.

In 2005, we at CLEO made the first firm identification (significance \(> 6\sigma\)) of \(h_c\) in the reaction

\[
\psi(2S) \rightarrow \pi^0 h_c, \; h_c \rightarrow \gamma \eta_c,
\]

in an analysis of 3.08 million \(\psi(2S)\) decays \([5]\).

In 2008, we repeated our measurement with 8 times larger luminosity, and 24.5 million \(\psi(2S)\) \([6]\). As before, data were analyzed in two ways. In the inclusive analysis, the photon energy, \(E_\gamma\), was loosely constrained, but the decay products of \(\eta_c\) were not identified. In the exclusive analysis, instead of constraining \(E_\gamma\) fifteen hadronic decay channels of \(\eta_c\) were measured. As shown in Fig. 4, \(h_c\) was observed with significance \(> 13\sigma\). The total number of events was \(N(h_c) = 1146 \pm 118\) from inclusive analysis, and \(N(h_c) = 136 \pm 14\) from exclusive analysis. The results from inclusive and exclusive analyses were consistent. The precision results were

\[
M(h_c) = 3525.28 \pm 0.19 \pm 0.12\text{ MeV},
\]

\[
\mathcal{B}_1 \times \mathcal{B}_2 = (4.19 \pm 0.32 \pm 0.45) \times 10^{-4}.
\]

Thus, \(h_c(1^1P_1)\) is now firmly established.

If it is assumed that \(M(3P)\) is identical to the centroid of the triplet–P states, \(\langle M(3P_J) \rangle = (5M(\chi_{c2}) + 3M(\chi_{c1}) + M(\chi_{c0}))/9 = 3525.30 \pm 0.04\) MeV, then the above \(M(h_c)\) leads to the hyperfine splitting,

\[
\Delta M_{hf}(1P)_{hc} = \langle M(3P_J) \rangle - M(1^P_1) = 0.02 \pm 0.23\text{ MeV},
\]  \tag{4}
FIGURE 4. The recoil mass of $\pi^0$ in the decay $\psi(2S) \rightarrow \pi^0 h_c$. (left) Full and background subtracted spectra for inclusive analysis. (right) Spectrum of exclusive analysis.

but, $\langle M(3P_J) \rangle_{0,1,2} \neq M(3P)!

The centroid $\langle M(3P_J) \rangle$ is a good measure of $M(3P)$ only if the spin–orbit splitting between the states $3P_2$, $3P_1$, and $3P_0$ is perturbatively small. It is obviously not so. The splitting, $M(3P_2) - M(3P_0) = 142$ MeV, is not small. Further, the perturbative prediction is that

$$M(3P_1) - M(3P_0) = \frac{5}{2} \left[ M(3P_2) - M(3P_1) \right] = 114 \text{ MeV},$$

while the experimental value is

$$M(3P_1) - M(3P_0) = 96 \pm 1 \text{ MeV}.$$ 

This is a 18 MeV difference! So we are obviously not in the perturbative regime.

This leads to serious questions.

• What mysterious cancellations are responsible for the wrong estimate of $M(3P)$ giving the expected answer that

$$\Delta M_{hf}(1P) = 0.$$ 

• Or, is it possible that the expectation is wrong? Is it possible that the hyperfine interaction is not entirely a contact interaction?

• Potential model calculations are not of much help because they smear the potential at the origin in order to be able to do a Schrödinger equation calculation.

• Can Lattice help? So far we have no lattice predictions with sufficient precision.

$\eta_b(1S_0)$, Hyperfine Interaction Between $b$–Quarks

The $b\bar{b}$ bottomonium system is, in principle, the best one to study the fundamental aspects of the hyperfine interaction between quarks. Unfortunately, until last year we had no knowledge of the hyperfine interaction between $b$–quarks. The spin–triplet $\Upsilon(13S_1)$ state of bottomonium was discovered in 1977, but its partner, the spin–singlet $\eta_b(1S_0)$ ground state of bottomonium, was not identified for thirty years, mainly because of the difficulty in observing weak M1 radiative transitions. There were many pQCD based theoretical predictions which varied all over the map, with $\Delta M_{hf}(1S_0) = 35 - 100$ MeV, and $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma \eta_b) = (0.05 - 25) \times 10^{-4}$.

This has changed now. The $\eta_b(1S_0)$ ground state of the $|b\bar{b}\rangle$ Upsilon family has been finally identified! In July 2008, BaBar announced the identification of $\eta_b$ [7]. They analyzed the inclusive photon spectrum of

$$\Upsilon(3S) \rightarrow \gamma \eta_b(1S).$$
in their data for $120$ million $^3\chi_b(3S)$ ($28\text{ fb}^{-1}$ $e^+e^-$). BaBar’s success owed to their very large data set and a clever way of reducing the continuum background, a cut on the so-called thrust angle, the angle between the signal photon and the thrust vector of the rest of the event, $|\cos\theta_{\text{thrust}}|<0.7$. BaBar’s results were:

$$M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \text{ MeV},$$  
 $$\Delta M_{hf}(1S)_b = 71.4^{+3.1}_{-2.3} \pm 2.7 \text{ MeV},$$ 
 $$\mathcal{B}(^3\chi_b(3S) \rightarrow \gamma \eta_b) = (4.8 \pm 0.5 \pm 0.6) \times 10^{-4}.$$

The significance of $\eta_b$ observation was $>10\sigma$. Recently, BaBar has also reported a $3.0\sigma$ identification of $\eta_b$ in $^3\chi_b(2S) \rightarrow \gamma \eta_b$ [7].

Any important discovery requires confirmation by an independent experiment. At CLEO we had data for only $5.9$ million $^3\chi_b(3S)$, i.e., about $20$ times less than BaBar. But we have better photon energy resolution, and we have been able to improve on BaBar’s analysis technique. We make three improvements. We make very detailed analysis of the large continuum background under the resonance photon peaks. We determine photon peak shapes by analyzing background from peaks in background–free radiative Bhabhas and in exclusive $^1\chi_b$ decays. And we make a joint fit of the full data in three bins of $|\cos\theta_{\text{thrust}}|$, covering the full range $|\cos\theta_{\text{thrust}}| = 0 - 1.0$ (see Fig. 5). Monte-Carlo simulations show that the joint fit procedure leads to an average increase of the significance of an $\eta_b$ signal by $\sim 20\%$ over accepting only events with $|\cos\theta_{\text{thrust}}|<0.7$. So, despite our poorer statistics, we have succeeded in confirming BaBar’s discovery with significance level $\sim 4\sigma$. The results have been submitted for publication [8].

Our results are:

$$M(\eta_b) = 9391.8 \pm 6.6 \pm 2.0 \text{ MeV},$$  
 $$\Delta M_{hf}(1S)_b = 68.5 \pm 6.6 \pm 2.0 \text{ MeV},$$ 
 $$\mathcal{B}(^3\chi_b(3S) \rightarrow \gamma \eta_b) = (7.1 \pm 1.8 \pm 1.3) \times 10^{-4}.$$

The results agree with those of BaBar. The average of our and BaBar’s results for the hyperfine splitting is

$$\langle \Delta M_{hf}(1S)_b \rangle = M(^3\chi_b(1S)) - M(\eta_b) = 69.4 \pm 2.8 \text{ MeV}.$$

A recent unquenched lattice calculation predicts (NRQCD with $u,d,s$ sea quarks) $\Delta M_{hf}(1S)_b = 61 \pm 14 \text{ MeV}$. A quenched lattice calculation (chiral symmetry and $s,c$ sea quarks) predicts $\Delta M_{hf}(1S)_b = 70 \pm 5 \text{ MeV}$. Thus, as far as the hyperfine splitting for the $|b\bar{b}\rangle$ is concerned, lattice calculations appear to be on the right track [9].
For more details on $\eta_b$ analysis by CLEO see the talk by S. Dobbs in the parallel session 7C [10].

**Hyperfine Splittings Measurements**

To summarize, we now have well–measured experimental results for several hyperfine splittings, with significant contributions from CLEO measurements.

| $|c\bar{c}|$ Charmonium: | $\Delta M_{h_c}(1S) = 116.4 \pm 1.2$ MeV, $\Delta M_{h_c}(2S) = 49 \pm 4$ MeV, $\Delta M_{h_c}(1P) = 0.02 \pm 0.23$ MeV, |
| $|b\bar{b}|$ Bottomonium: | $\Delta M_{h_b}(1S) = 69.4 \pm 2.8$ MeV. |

In charmonium, we do not have satisfactory understanding of the variation of hyperfine splitting for the S–wave radial states, and for P–wave state.

- For charmonium, we do not have any unquenched lattice predictions, at present.
- For bottomonium, lattice predictions are available, and they appear to be on the right track.
- For neither charmonium nor bottomonium there are any reliable predictions of transitions strength, particularly for forbidden M1 transitions.

Much remains to be done. On the experimental front it is very important to identify for bottomonium the allowed M1 transition, $\Upsilon(1S) \rightarrow \gamma\eta_b(1S)$, and to identify the bottomonium singlet P–state, $h_b(^3P_1)$. On the theoretical front one would like to see unquenched lattice calculations for charmonium singlets, and, of course, for transition strengths.

**MEASUREMENTS OF THE DECAY BRANCHING FRACTIONS OF CHARMONIUM AND BOTTOMONIUM STATES**

**Search for Exclusive Decays of $\eta_c'(2S')$**

Recently, CLEO has performed a search for the decay $\psi(2S) \rightarrow \gamma\eta_c'(2S)$ in a sample of 26 million $\psi(2S)$ events [11]. Expected $E_\gamma = 48$ MeV. Eleven exclusive decay modes, $\eta_c'(2S') \rightarrow$ hadrons, $(\pi, K, \eta, \eta')$ with up to 6 particles (charged and neutral) were reconstructed, but no signals of $\eta_c'(2S)$ were observed in any of the decay modes, or in their sum.

The product branching fraction upper limits were determined for the individual modes, and they are at the level of $(4\rightarrow15) \times 10^{-6}$. These upper limits are an order of magnitude smaller than expected by assuming that the partial widths for $\eta_c'(2S)$ decays are the same as for $\eta_c(1S)$. Thus, so far $K\bar{K}K\pi$ is the only decay mode in which $\eta_c'(2S)$ has been identified.

**Evidence for Exclusive Decay of $h_c(1P)$ to Multipions**

Now that $h_c$ has been discovered, CLEO has searched for hadronic decays of $h_c$ in multipion channels [12]. Of the three decays investigated, only one, the five pion decay $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$, is found to have a statistically significance signal, with $B(\psi(2S) \rightarrow h_c) \times B(h_c \rightarrow 2(\pi^+\pi^-)\pi^0) = (1.9^{+0.7}_{-0.5}) \times 10^{-5}$ (see Table 1). This is $\sim 5\%$ of $B(\psi(2S) \rightarrow h_c) \times B(h_c \rightarrow \gamma\eta_c) = (4.19 \pm 0.32 \pm 0.45) \times 10^{-4}$.

**Observation of $J/\psi \rightarrow 3\gamma$**

No $3\gamma$ decay of a meson has been observed before. In the lowest order, $3\gamma$ decay is a QED process, and the predicted ratio $\mathcal{B}(J/\psi \rightarrow 3\gamma)/\mathcal{B}(J/\psi \rightarrow e^+e^-) = 5.3 \times 10^{-4}$, which is independent of charm quark mass and wave function, leads to $\mathcal{B}(J/\psi \rightarrow 3\gamma) = 3.2 \times 10^{-5}$. QCD radiative corrections, which are not reliably known, may modify the prediction.
TABLE 1. Results for exclusive decays of \( h_c(1P) \) to multipoles.

| Mode          | Efficiency (%) | Yield   | \( B(\psi(2S) \to h_c) \times B(h_c \to n(n\pi^+\pi^-)p^0) \times 10^5 \) |
|---------------|---------------|---------|-----------------------------------------------------------------|
| \( \pi^+\pi^-\pi^0 \) | 27.0%         | \( 1.6^{+5.7}_{-3.5} \) | \(< 0.2 \) (90%)                                                |
| \( 2(\pi^+\pi^-)\pi^0 \) | 18.8%         | \( 97^{+23}_{-22} \) | \( 1.88^{+0.48+0.47}_{-0.42-0.16} \) (significance \( \sim 4\sigma \)) |
| \( 3(\pi^+\pi^-)\pi^0 \) | 11.5%         | \( 35 \pm 26 \) | \(< 2.5 \) (90%)                                               |

FIGURE 6. Observation of \( J/\psi \to 3\gamma \). Background subtracted data and signal Monte-Carlo distributions for variable \( \chi^2/dof \) of kinematic fit. The signal and background normalization regions are shown by full horizontal, \( \chi^2/dof = 0 \) (signal), \( \chi^2/dof = 5 \) – 20 (background) lines.

To search for \( 3\gamma \) decay of \( J/\psi \), CLEO has used a QED background free sample of 9.6 million \( J/\psi \) obtained by \( \pi^+\pi^- \) tagging in the decay \( \psi(2S) \to (\pi^+\pi^-)/J/\psi \) [13]. Kinematic fitting of the data leads to the result, \( B(J/\psi \to 3\gamma) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5} \) (Significance \( \sim 6\sigma \)). Fig. 6 shows background subtracted data and signal Monte-Carlo distributions.

**Precision Measurements of Branching Fractions**

Using the data set of **26 million** \( \psi(2S) \), CLEO has made precision measurements of decays of \( \psi(2S) \), \( J/\psi(1S) \), and \( \chi_{cJ}(1P) \) [14]. Among the decays measured are:

- \( \psi(2S), J/\psi \to \gamma h \ (h = \pi^0, \eta, \eta' ) \)
- \( \psi(2S), J/\psi \to \gamma gg \)
- \( \chi_{cJ} \to \gamma X \ (X = \rho, \Lambda, \Sigma, \Xi) \) (6 decay modes)
- \( \chi_{cJ} \to h^+h^-h^0h^0, h^+h^-h^0h^0 \) (\( h^0 = \pi^0, K^0, h^0 = 0, \eta, \eta', K^0 \)) (12 decay modes)
- \( \chi_{cJ} \to \gamma \gamma, \gamma V \ (V = \rho, \omega, \phi) \)

Many of these decays have been measured for the first time, and others have greater precision than the results in the literature. Some of the interesting theoretical problems that the branching fractions pose are:

- The ratio \( B(\psi(nS) \to \gamma \eta)/B(\psi(nS) \to \gamma \eta') \) is expected to be equal for 1S and 2S states; CLEO measured an order of magnitude difference between the two, \( (21.1 \pm 0.9\%) \) for 1S, and \(< 1.8\% \) for 2S.
- The measured rates \( B(\chi_{c1} \to \gamma \rho) \) and \( B(\chi_{c1} \to \gamma \omega) \) are significantly higher than those predicted by pQCD.
- The ratio \( B(\chi_{c0} \to \gamma \gamma)/B(\chi_{c2} \to \gamma \gamma) \) disagrees with pQCD expectations. This result provides experimental confirmation of the inadequacy of the present first order radiative corrections.

**Hadronic Decays of \( \chi_{bJ}(1P, 2P) \), and Inclusive \( \chi_{bJ}(1P, 2P) \) Decays to Open Charm**

No hadronic decays of \( \chi_{bJ}(1P) \) have been measured before. For \( \chi_{bJ}(2P) \) the only hadronic decays measured so far were \( \chi_{bJ}(2P) \to \pi \pi \chi_{bJ}(1P) \) and \( \chi_{bJ}(2P)_{b1,2} \to \omega \chi(1S) \).
At CLEO we have made the first measurements of 14 different decays of $\psi(1P, 2P)$ to light hadrons [15]. Up to 12 particles were detected. The branching fractions for the corresponding decays of $\chi_{b1,2}(1P)$ and $\chi_{b1,2}(2P)$ were found to be nearly equal. The ratios between decays to $n$ charged pions and $(n - 2)$ charged +2 neutral pions were found to approximately follow the expectations based on combinatorics.

CLEO also measured the inclusive decays of $\psi(nP)$ to $D^0 + X$ [16]. The enhanced rates for $\psi(1P, 2P)$ to $D^0 + X$ were found to be consistent with NRQCD predictions.

SUMMARY

CLEO data at $\psi(2S)$ and $\Upsilon(1S, 2S, 3S)$ resonances were analyzed. The prominent results are the following.

- Observation of $\eta_c'(2S)$ in $\gamma\gamma$ fusion, and its mass measurement. Search for $\eta_c'(2S)$ in exclusive decays, and upper limit measurements for decay branching fractions.
- Observation of $h_c(1P)$ in $\psi(2S) \rightarrow \pi^0 h_c$, and precision measurement of its mass. Evidence of $h_c$ decay in multi-pion exclusive final state.
- Confirmation of $\eta_b(1S)$ observation, and measurement of mass of $\eta_b$ and decay branching fraction $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\eta_b)$.
- Observation of decay $J/\psi \rightarrow 3\gamma$ (first observation of meson decay in $3\gamma$).
- Precision measurements of decay branching fractions of $\psi(2S)$, $J/\psi(1S)$, and $\chi_{cJ}(1P)$ charmonium states, and $\chi_{bJ}(1P, 2P)$ bottomonium states. Many of these decays have been measured for the first time, and others have much greater precision than the results in the literature.

There is a rich program of hadronic physics at CLEO; too extensive to cover it all in one talk. There are also quite a few analyses in a preliminary stage. Expect new results in the coming years.

REFERENCES

1. C. Amsler et al. (Particle Data Group), Phys. Lett. B 667, (2008) 1 and 2009 partial update for the 2010 edition.
2. S. K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. 89, (2002) 142001.
3. D. M. Asner et al. (CLEO Collaboration), Phys. Rev. Lett. 92, (2004) 142001.
4. B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 92, (2004) 142002.
5. J. L. Rosner et al. (CLEO Collaboration), Phys. Rev. Lett. 95, (2005) 102003.
6. S. Dobbs et al. (CLEO Collaboration), Phys. Rev. Lett. 101, (2008) 182003.
7. B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 101, 071801 (2008); B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 103, 161801 (2009).
8. G. Bonvicini et al. (CLEO Collaboration), submitted to Phys. Rev. Lett.; arXiv:0909.5474[hep-ex].
9. A. Gray et al., (HPQCD and UKQCD Collaborations), Phys. Rev. D 72, 094507 (2005); T. Burch and C. Ehmann, Nucl. Phys. A 797, 33 (2007); T. W. Chiu, T. H. Hsieh, C. H. Huang and K. Ogawa (TWQCD Collaboration), Phys. Lett. B 651, 171 (2007).
10. S. Dobbs, this proceedings; arXiv:1001.2238[hep-ex].
11. D. Cronin–Hennerty et al. (CLEO Collaboration), Submitted to Phys. Rev. D.; arXiv:0910.1324v1[hep-ex].
12. G.S. Adams et al. (CLEO Collaboration), Phys. Rev. D 80, 051106(R) (2009).
13. G.S. Adams et al. (CLEO Collaboration), Phys. Rev. Lett. 101, 101801 (2008).
14. (CLEO Collaboration), Phys. Rev. D 79, 111101(R) (2009); Phys. Rev. D 78, 032012 (2008); Phys. Rev. D 80, 072002 (2009); Phys. Rev. D 78, 031101(R) (2008); Phys. Rev. D 79, 072007 (2009); Phys. Rev. D78,092004(2008); Phys. Rev. D 78, 191501(R) (2008); Phys. Rev. Lett. 101, 151801 (2008).
15. D.M. Asner et al. (CLEO Collaboration), Phys. Rev. D 78, 091103(R) (2008).
16. R.A. Briere et al. (CLEO Collaboration), Phys. Rev. D 78, 092007 (2008).