HEAVY QUARKONIA
Recent Results from CLEO

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1 Introduction

Before it stopped data taking in 2008, CLEO had accumulated a large amount of e^+e^- data in the bottomonium and charmonium regions, as shown in Table 1. These data have led to valuable contributions in the spectroscopy of both $|c\bar{c}\rangle$ and $|b\bar{b}\rangle$ quarkonia, and their continuing analysis is leading to new physics results. In this presentation I want to describe some of the results obtained since HADRON 2009 [1]. More than a dozen papers on spectroscopy have been published since then, and my choice for this time-limited presentation is necessarily a subjective one.

Charmonium region	**Bottomonium region**
$\psi(2S, 3686)$: 54 pb^{-1}, $\sim$ 27 million $\psi(2S)$	$\Upsilon(1S)$: 1056 pb^{-1}, 20.8 million $\Upsilon(1S)$
$\psi(3770)$: 818 pb^{-1}, $\sim$ 5 million $\psi(3770)$	$\Upsilon(2S)$: 1305 pb^{-1}, 9.3 million $\Upsilon(2S)$
$\psi(4170)$: 586 pb^{-1}, $\sim$ 5 million $\psi(4170)$	$\Upsilon(3S)$: 1378 pb^{-1}, 5.9 million $\Upsilon(3S)$
$\sqrt{s} = 3670$ MeV : 21 pb^{-1}	$\Upsilon(4S)$: 9400 pb^{-1}, 15.4 million $B\bar{B}$
$\sqrt{s} = 4040$ MeV : 20.7 pb^{-1}	$\sqrt{s} = 10,520$ MeV : 4500 pb^{-1}
$\sqrt{s} = 4260$ MeV : 13.2 pb^{-1}	Off $\Upsilon(nS)$: 800 pb^{-1}

Table 1: CLEO data in the charmonium and bottomonium regions

2 Hyperfine Interaction in Quarkonia

One of our major interests at CLEO during the last five years has been in the study of the hyperfine interaction in quarkonia, and our investigations into it have continued to yield new insights into the subject.

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The hyperfine or spin-spin interaction in $|c\bar{c}\rangle$ and $|b\bar{b}\rangle$ quarkonia leads to the hyperfine splitting between spin-triplet and spin-singlet states, which is defined as

$$\Delta M_{hf}(nL) = M(n^3L) - M(n^1L)$$

where n and L are the principal and angular momentum quantum numbers.

For a purely Coulombic central potential, as for $|e^+e^-\rangle$ positronium, for $|q\bar{q}\rangle$ quarkonium the hyperfine interaction is a contact interaction, and leads to the predictions —

$$\Delta M_{hf}(nS) = M(n^3S_1) - M(n^1S_0) = \frac{32\pi\alpha_s(m_q)}{9}(\psi(0)/m_q)^2, \quad L = 0$$

$$\Delta M_{hf}(nL) = M(n^3L) - M(n^1L) = 0, \qquad L \neq 0$$

where $\alpha_s(m_q)$ is the strong coupling constant for quark mass m_q, and $\psi(0)$ is the wave function at the origin.

The interest for quarkonia is in determining the extent to which these predictions are valid, because for quarkonia the central potential has the confinement part in addition to the Coulombic part, and the charm and beauty quarks, which have different masses, bring in different relativistic and higher order effects.

As is well known, in e^+e^- annihilation the spin-triplet-S wave states, called ψ_c and Υ_b, $^3S_1(J^{PC} = 1^{--})$ are directly produced, and the spin-triplet P-wave states, $^3P_J(J^{PC} = 0^{++}, 1^{++}, 2^{++})$, called χ_{cJ}, χ_{bJ}, are strongly excited by E1 radiative transitions from the triplet S states. In contrast, the M1 radiative transitions to the spin-singlet states, $^1S_0(J^{PC} = 0^{-+})$, called η_c and η_b, and $^1P_1(J^{PC} = 1^{+-})$, called h_c and h_b, are much weaker and much more difficult to identify because of their close proximity to the triplet states. As a result, for more than two decades after the discovery of $J/\psi(1^3S_1)_{c\bar{c}}$, $\psi(2^3S_1)_{c\bar{c}}$, and $\Upsilon(n^3S_1)_{b\bar{b}}(n = 1, 2, 3, 4)$, the only singlet state which was successfully identified was $\eta_c(1^1S_0)$, and the only hyperfine splitting which was known was $\Delta M_{hf}(1S)_{c\bar{c}} = 116.6 \pm 1.2$ MeV [2]. As a result, it was not known how the hyperfine interaction between quarks changes with greater exposure to the confinement potential with increasing redius (1S versus 2S), with increasing angular momentum (S-wave versus P-wave), and increasing quark mass (c-quarks versus b-quarks). Great progress in answering these questions has been recently made by B-factories and CLEO in challenging new measurements. Belle identified $\eta_c'(2^1S_0)$ in B-decays [3], and it was confirmed by CLEO [4] and BaBar [5] in two photon formation. CLEO [6] identified $h_c(1^1P_1)$ in $\psi(2S)$ decay. BaBar [7] identified $\eta_b(1^1S_0)$ in $\Upsilon(3S)$ decays, and it was confirmed by CLEO [8]. Identification of $\eta_c(3^1S_0)$ and $h_c(2^1P_1)$, which lie above the $D\overline{D}$ break-up threshold, and $\eta_b(2, 3^1S_0)$ and $h_b(1, 2^1P_1)$ remained as challenges[2].

[2]For the breaking news on the discovery of $h_b(1, 2^1P_1)$ see Ref [14].

3 New Results for P-wave Singlet State $h_c(1^1P_1)$

CLEO reported the discovery of h_c in 2005 [6], and the precision measurement of its mass in 2008 [9],

$$\text{CLEO [2008]}: \; M(h_c, 1^1P_1) = 3525.28 \pm 0.19(\text{stat}) \pm 0.12(\text{syst}) \text{ MeV}.$$

It is extremely gratifying that BES III [10] has now confirmed this, with the result:

$$\text{BES III [2010]}: \; M(h_c, 1^1P_1) = 3525.40 \pm 0.13(\text{stat}) \pm 0.18(\text{syst}) \text{ MeV}.$$

The centroid of the ^3P_J states ($\chi_{0,1,2}$) is known to be [2]

$$\langle M(^3P_J)\rangle = [5M(^3P_2) + 3M(^3P_1) + M(^3P_0)] = 3525.30 \pm 0.04 \text{ MeV}.$$

If the ^3P_J states centroid mass $\langle M(^3P_J)\rangle$ above is identified as the mass $M(^3P)$, then the hyperfine splittings are

$$\text{CLEO:} \quad \Delta M_{hf}(1P)_{c\bar{c}} = +0.02 \pm 0.23 \text{ MeV, and}$$

$$\text{BES III:} \quad \Delta M_{hf}(1P)_{c\bar{c}} = -0.10 \pm 0.22 \text{ MeV}.$$

However, it must be pointed out that the identification of the centroid is only valid if the spin-orbit splitting between the ^3P_J states in perturbatively small. This is hardly the case here with $M(^3P_2) - M(^3P_0) = 141.45 \pm 0.32$ MeV, and the perturbative prediction $M(^3P_1) - M(^3P_0) = (5/2) \times [M(^3P_2) - M(^3P_1)] = 114$ MeV is 20% larger than the experimental result = 96 MeV. Why then is $\Delta M_{hf}(1P)$ so very close to zero? It is a mystery.

3.1 Beyond the discovery of h_c [11]

In our h_c discovery and mass papers in the decay

$$\psi(2S) \to \pi^0 h_c, \; h_c \to \gamma\eta_c$$

we made inclusive analyses of the π^0 recoil spectrum by either constraining the γ energy or η_c mass. As a result we could only determine the product branching fraction $\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c)$.

BES III data for 100 million $\psi(2S)$ allowed them to observe h_c directly in the π^0 recoil spectrum. It occured to us at CLEO recently to also attempt to also identify h_c directly in the π^0 recoil spectrum despite our factor four smaller 25.9 million $\psi(2S)$ sample. By rejecting very asymmetric $\pi^0 \to 2\gamma$ decays, as shown in Fig. 1, we were successful in identifying h_c. Our result is in excellent agreement with the BES III result [10]

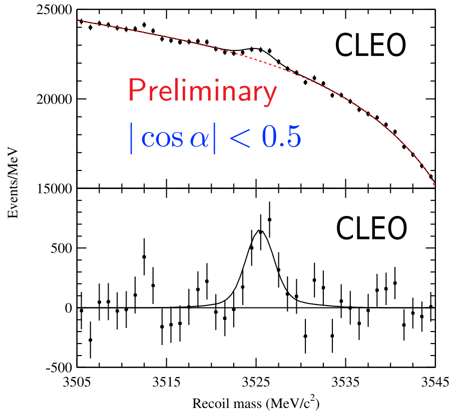


Figure 1: New CLEO result for the inclusive analysis of $\psi(2S) \to \pi^0 h_c$

CLEO: $\mathcal{B}[\psi(2S) \to \pi^0 h_c] = (9.0 \pm 1.5 \pm 1.2) \times 10^{-4}$ [11]

BES III: $\mathcal{B}[\psi(2S) \to \pi^0 h_c] = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$ [10]

Average: $\mathcal{B}[\psi(2S) \to \pi^0 h_c] = (8.7 \pm 1.2) \times 10^{-4}$

3.2 Hadronic decays of h_c [12]

The CLEO result [9] $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) = (4.19 \pm 0.55) \times 10^{-4}$ has also been confirmed by BES III [10] with $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) = (4.58 \pm 0.64) \times 10^{-4}$, and the average is $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) = (4.39 \pm 0.42) \times 10^{-4}$. Combined with $\mathcal{B}_1(\psi(2S) \to \pi^0 h_c) = (8.7 \pm 1.2) \times 10^{-4}$, we obtain $\mathcal{B}_2(h_c \to \gamma\eta_c) = (50.5 \pm 8.5)\%$. Therefore, we expect that the remaining 50% decays of h_c must be to hadrons. This suggests that decays to odd number of pions may be an important component of the hadronic decays. We have therefore measured [12]

$$\psi(2S) \to \pi^0 h_c,\ h_c \to (\pi^+\pi^-)\pi^0,\ n = 1, 2, 3$$

Unfortunately, no significant yield was found for 3 or 7 pion final states. Only a small 5 pion transition was observed with

$$\mathcal{B}(h_c \to 2(\pi^+\pi^-)\pi^0) = (1.9^{+0.7}_{-0.5}) \times 10^{-5}$$

This leaves us with the interesting question of what are the $\sim 50\%$ unobserved hadronic decays of h_c.

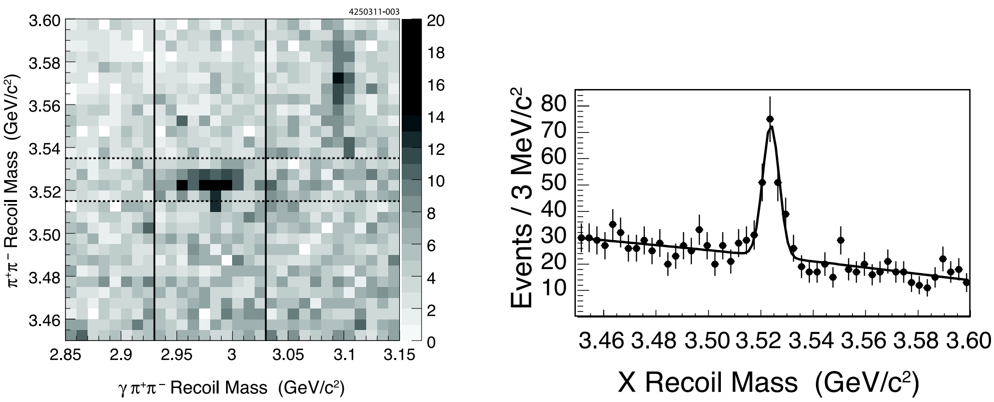


Figure 2: Illustrating the identification of h_c in $e^+e^-(4170) \to \pi^+\pi^- h_c$. Left: two dimensional plot showing h_c enhancement at the intersection of $M(\eta_c) \approx 2.98$ GeV and $M(h_c) \approx 3.52$ GeV. Right: distribution of events in the box marked in the two dimensional plot as function of $\pi^+\pi^-$ recoil mass.

3.3 Discovery of a new mode of h_c production [13]

CLEO has made an important discovery in identifying h_c formation in the $\pi^+\pi^-$ decay of $\psi(4170)$ above the $D\overline{D}$ threshold [13]. Using 586 pb^{-1} of e^+e^- annihilation data at $\sqrt{s} = 4170$ MeV we observe a 10σ signal for h_c in the decay

$$e^+e^-(4170) \to \pi^+\pi^- h_c(1P),$$

with $h_c \to \gamma\eta_c, \eta_c \to 12$ decay modes[3].

In the two dimensional plot shown in Fig. 2 the h_c signal is clearly seen in $\pi^+\pi^-$ recoil mass at the intersection of its radiative decay to η_c at 2.98 GeV. (The enhancement at 3.1 GeV is due to J/ψ.) In the projection h_c is seen as a strong enhancement over a featureless background. The production cross section is a very healthy 15.6 ± 4.2 pb. The paper has been accepted for publication in the PRL.

Our discovery of the population of $h_c(1P)$ in e^+e^- annihilations above the $D\overline{D}$ threshold of charmonium has led the Belle collaboration to search for $h_b(1P, 2P)$ in e^+e^- annihilations at $\sqrt{s} = 10.685$ GeV using the same technique of recoil against $\pi^+\pi^-$. They have achieved dramatic success, as you have already heard in their plenary presentation [14].

[3] $\eta_c \to 2(\pi^+\pi^-), 2(\pi^+\pi^-)2\pi^0, 3(\pi^+\pi^-), K^\pm K^0_S\pi^\mp, K^\pm K^0_S\pi^\mp\pi^+\pi^-, K^+K^-\pi^0, K^+K^-\pi^+\pi^-, K^+K^-\pi^+\pi^-\pi^0, K^+K^-2(\pi^+\pi^-), 2(K^+K^-), \eta\pi^+\pi^-$, and $\eta 2(\pi^+\pi^-)$.

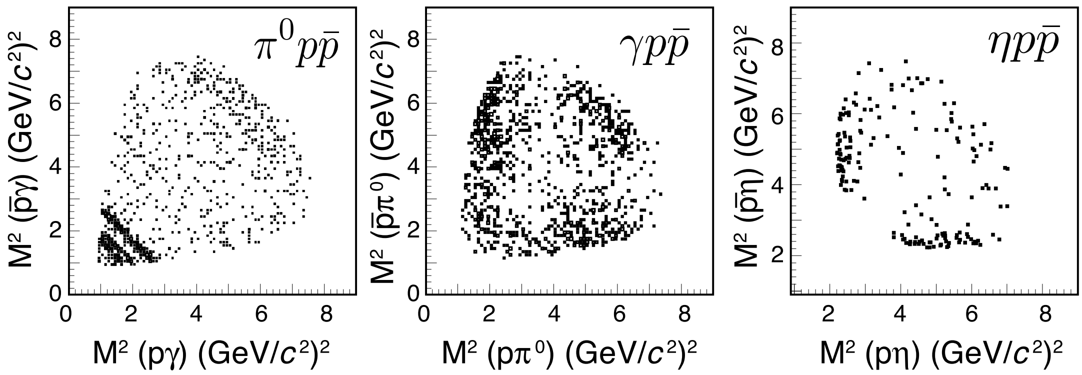


Figure 3: Dalitz plots for the three decays, $\psi(2S) \to \pi^0 p\overline{p}, \gamma p\overline{p}$, and $\eta p\overline{p}$.

4 Hadronic Decays of P-wave States of Bottomonium [16]

Compared to charmonium very few decays of bottomonium states have ever been measured. Earlier we reported on the first measurements of $\chi_{bJ}(1P, 2P), J = 0, 1, 2$, decays to fourteen exlusive hadronic final states [15].

$$\Upsilon(2S, 3S) \to \gamma\chi_{bJ}(1P, 2P), \quad \chi_{bJ}(1P, 2P) \to \text{hadrons}$$

We have now made the first measurements of

$$\Upsilon(2S, 3S) \to \gamma\chi_{bJ}(1P) \to \gamma\gamma\Upsilon(1S) \text{ [16]}$$

The results from $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$ are

$$\mathcal{B}[\chi_{bJ}(1P) \to \gamma\Upsilon(1S)] \text{ in } \% = 1.73 \pm 0.35(\chi_0),\ 33.0 \pm 2.6(\chi_1),\ 18.5 \pm 1.4(\chi_2)$$

These measurements lead to much improved determinations of

$$\mathcal{B}[\Upsilon(3S) \to \gamma\chi_{b1}(1P)] = (1.63 \pm 0.46) \times 10^{-3} \text{ (CLEO)}, \quad < 1.9 \times 10^{-3} \text{ [2,PDG]}$$

$$\mathcal{B}[\Upsilon(3S) \to \gamma\chi_{b2}(1P)] = (7.7 \pm 1.3) \times 10^{-3} \text{ (CLEO)}, \quad < 20.3 \times 10^{-3} \text{ [2,PDG]}$$

5 Decays of $\psi(2S)$ to $p\overline{p} + \gamma$, π^0 and η, and search for baryonium in $\psi(2S)$ and J/ψ decays [17]

This CLEO investigation [17] was motivated by the longstanding claim by BES for the interpretation of an observed near-threshold enhancement in the decay, $J/\psi \to \gamma(p\overline{p})$ as evidence for a weakly bound proton-antiproton resonance, $\mathrm{R_{thr}}$, with $M(p\overline{p}) = 1859^{+6}_{-27}$ MeV, $\Gamma < 30$ MeV, and

$$\mathcal{B}(J/\psi \to \gamma\mathrm{R_{thr}}) \times \mathcal{B}(\mathrm{R_{thr}} \to p\overline{p}) = (7.0^{+1.9}_{-0.9}) \times 10^{-5}.$$

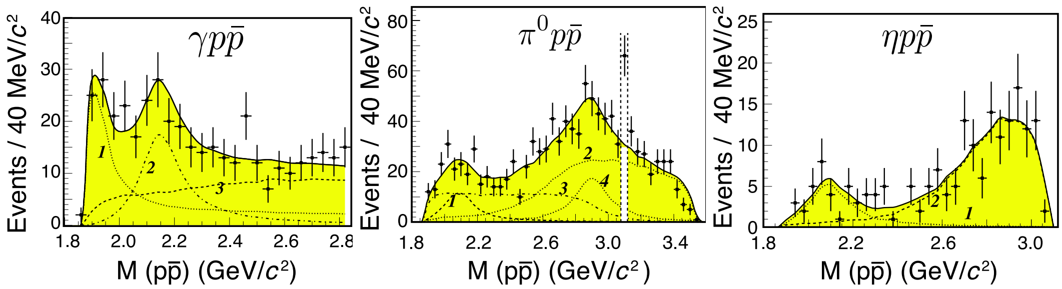


Figure 4: Event projections as function of $M(p\bar{p})$ in the decays $\psi(2S) \to \pi^0 p\bar{p}$, $\gamma p\bar{p}$, and $\eta p\bar{p}$. The curves show contributions of different intermediate resonances and their total.

Quantity	CLEO (10^{-5})	PDG10 (10^{-5})
$\mathcal{B}(\psi(2S) \to \gamma p\bar{p})$	4.18 ± 0.3	2.9 ± 0.6
$\mathcal{B}(\psi(2S) \to \pi^0 p\bar{p})$	15.4 ± 0.9	13.3 ± 1.7
$\mathcal{B}(\psi(2S) \to \eta p\bar{p})$	5.6 ± 0.7	6.0 ± 1.2
$\mathcal{B}(\psi(2S) \to \gamma f_2(1950)) \times \mathcal{B}(f_2(1950) \to p\bar{p})$	1.2 ± 0.2	
$\mathcal{B}(\psi(2S) \to \gamma f_2(2150)) \times \mathcal{B}(f_2(2150) \to p\bar{p})$	0.72 ± 0.18	
$\mathcal{B}(\psi(2S) \to \pi^0 R_1(2100)) \times \mathcal{B}(R_1(2100) \to p\bar{p})$	1.1 ± 0.4	
$\mathcal{B}(\psi(2S) \to \pi^0 R_2(2900)) \times \mathcal{B}(R_2(2900) \to p\bar{p})$	2.3 ± 0.7	
$\mathcal{B}(\psi(2S) \to \eta R_1(2100)) \times \mathcal{B}(R_1(2100) \to p\bar{p})$	1.2 ± 0.4	
$\mathcal{B}(\psi(2S) \to \bar{p} N_1^*(1440)) \times \mathcal{B}(N_1^*(1440) \to p\pi^0)$	8.1 ± 0.8	
$\mathcal{B}(\psi(2S) \to \bar{p} N_2^*(2300)) \times \mathcal{B}(N_2^*(2300) \to p\pi^0)$	4.0 ± 0.6	
$\mathcal{B}(\psi(2S) \to \bar{p} N^*(1535)) \times \mathcal{B}(N^*(1535) \to p\eta)$	4.4 ± 0.7	

Table 2: Branching fractions determined for $\psi(2S)$ decays into various intermediate N^* and meson states R_n which decay to $p\bar{p}$.

We argued that if the baryonium resonance was real, it should also be seen in $\psi(2S) \to \gamma(p\bar{p})$, and perhaps also in $\pi^0(p\bar{p})$ and $\eta(p\bar{p})$. Accordingly, we made a detailed analysis of our data set of 24.5 million $\psi(2S)$. The Dalitz plots in Fig. 3 show that a number of light quark resonances are excited in all three decays.

The structures observed in the Dalitz plots were analyzed via their projections as shown in Fig. 4. As listed in Table 2, branching fractions were determined for a number of baryon (N^*), and meson resonances (R) which decay into $p\bar{p}$. Most of these represent first such measurements. We note that among the intermediate states identified are $f_2(2150)$ and $N^*(2300)$ which have since been also observed by BES III [Hai-Bo Li at this conference].

We now turn to our results for the search for $p\bar{p}$ threshold enhancements. These are illus-

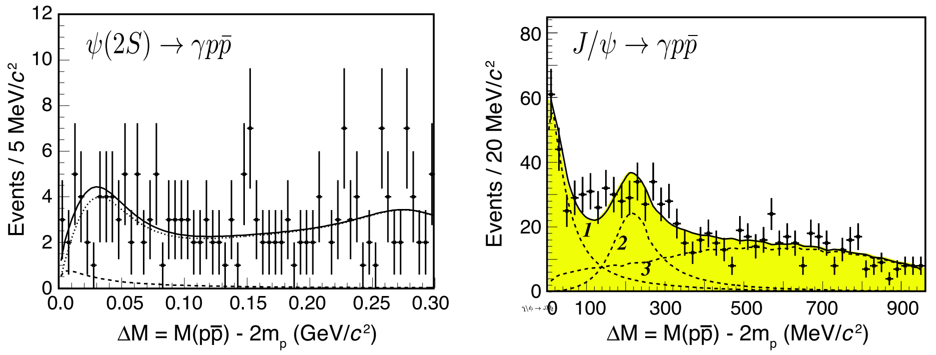


Figure 5: Event distributions as function of $\Delta M = M(p\overline{p}) - 2M_p$. left: $\psi(2S) \to \gamma p\overline{p}$; right: $J/\psi \to \gamma p\overline{p}$.

trated in Fig. 5 in terms of $\Delta M = M(p\overline{p}) - 2m_p$.

$\boldsymbol{\psi(2S) \to \gamma p\overline{p}}$: As shown in Fig. 5, we find no evidence for a threshold enhancement in $M(p\overline{p})$, and establish the upper limit for a resonance with BES parameters for $R_{\rm thr}$

$$\mathcal{B}(\psi(2S) \to \gamma \mathrm{R_{thr}}) \times \mathcal{B}(\mathrm{R_{thr}} \to p\overline{p}) < 1.6 \times 10^{-6}.$$

$\boldsymbol{J/\psi \to \gamma p\overline{p}}$: Using the data for 8.7 million J/ψ produced via $\psi(2S) \to \pi^+\pi^- J/\psi$, $\mathrm{R_{thr}}$ was also searched for in $J/\psi \to \gamma(p\overline{p})$.

As shown in Fig. 5, the observed threshold enhancement fitted in the region, $\Delta M = 0 - 900$ MeV leads to

$$M(\mathrm{R_{thr}}) = 1837 \pm 14\ \mathrm{MeV}, \Gamma(\mathrm{R_{thr}}) = 0^{+44}_{-0}\ \mathrm{MeV, and}$$

$$\mathcal{B}(J/\psi \to \gamma \mathrm{R_{thr}}) \times \mathcal{B}(\mathrm{R_{thr}} \to p\overline{p}) = (11.4^{+6.0}_{-4.0}) \times 10^{-5}.$$

BES III has recently confirmed [18] the existence of a resonance decaying into $\pi^+\pi^-\eta'$ with $M = 1836.5^{+6.4}_{-3.7}$ MeV and $\Gamma = 190 \pm 39$ MeV. Such a wide resonance could very well decay into $p\overline{p}$ above threshold, and account for the observed threshold enhancement. BES II and we had earlier proposed this possibility, but BES III makes no comment about it in their latest paper [18].

6 Decays of χ_{cJ} to $p\overline{p} + \pi^0, \eta$ and ω [19]

The χ_{cJ} states are strongly populated by E1 radiative decays from $\psi(2S)$. CLEO has recently made measurements of χ_{cJ} decays to $p\overline{p} + \pi^0, \eta, \omega$ [19]. The results are presented in

$\mathcal{B}_\chi \times 10^4$	χ_0		χ_1		χ_2	
	CLEO	PDG [2]	CLEO	PDG [2]	CLEO	PDG [2]
$\mathcal{B}(\chi_J \to p\overline{p}\pi^0)$	7.8 ± 0.7	5.7 ± 1.2	1.8 ± 0.2	1.2 ± 0.5	4.8 ± 0.5	4.7 ± 1.0
$\mathcal{B}(\chi_J \to p\overline{p}\eta)$	3.7 ± 0.5	3.7 ± 1.1	1.6 ± 0.3	< 1.6	1.8 ± 0.3	2.0 ± 0.8
$\mathcal{B}(\chi_J \to p\overline{p}\omega)$	5.6 ± 0.7		2.3 ± 0.4		3.7 ± 0.5	

Table 3: Branching fractions determined for χ_J decays to $p\overline{p}\pi^0$, $p\overline{p}\eta$, and $p\overline{p}\omega$.

Table 3. The errors in these results are factor > 2 smaller than in the previous measurements.

Both sets of measurements, $\psi(2S) \to p\overline{p} + \gamma, \pi^0, \eta$ in Sec. 5 and $\chi_{cJ} \to p\overline{p} + \pi^0, \eta, \omega$ in Sec. 6, are potentially of great value to the future $p\overline{p}$ experimentation at PANDA(GSI).

7 Multipole Admixtures in Dipole Transitions [20]

If the radiative transitions $\chi_{c1}, \chi_{c2} \to \gamma J/\psi$ are attributed to a single quark, the E1 transitions can have small M2 components, with $a_2 = M2/\sqrt{E_1^2 + M_2^2}$. Simple predictions are that $a_2(\chi_1) = -(E_\gamma/4m_c)(1+\kappa_c)$, and $a_2(\chi_2) = (-3/\sqrt{5})(E_\gamma/4m_c)(1+\kappa_c)$, where κ_c is the anomalous magnetic moment of the charm quark.

Previous attempts at SLAC and Fermilab E760/E835 to measure $a_2(\chi_1, \chi_2)$ were limited mainly by statistics, and had large errors.

CLEO has recently made a high statistics measurement [20], with the results

$$a_2(\chi_{c1}) = (-6.26 \pm 0.67) \times 10^{-2}, \text{ and } \; a_2(\chi_{c2}) = (-9.3 \pm 1.6) \times 10^{-2}.$$

The ratio, $a_2(\chi_{c2})/a_2(\chi_{c1}) = 1.49 \pm 0.30$ is consistent with $3/\sqrt{5} = 1.34$, justifying the hypothesis of a **single quark transition**.

For assumed $m_c = 1.5$ GeV, we get

$$\chi_{c1} : (1+\kappa_c) = 0.88 \pm 0.20, \quad \chi_{c2} : (1+\kappa_c) = 1.10 \pm 0.19.$$

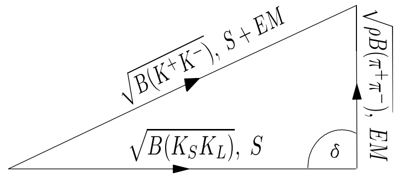
Both are consistent with **the anomalous magnetic moment of the charm quark,** $\kappa_c = 0$**.**

In a quenched lattice calculation the Jlab group predicts $a_2(\chi_{c1}) = (-20 \pm 6) \times 10^{-2}$, $a_2(\chi_{c2}) = (-39 \pm 7) \times 10^{-2}$, factors 3 to 4 larger than our measured values [21].

8 Interference in Strong and Electromagnetic Decays of $\psi(2S)$ to Pseudoscalar Pairs, $PP = \pi^+\pi^-, K^+K^-$ and K_SK_L [25]

Interest in final state interaction (FSI) phases originally arose from CP violation in K decays and B decays. However, it was discovered that large FSI phases are perhaps a general feature. Suzuki [22] and Rosner [23] have analyzed J/ψ decays into pseudoscalar-vector (PV) pairs, and pseudoscalar-pseudoscalar (PP) pairs, and find that the phase differences between strong and EM decay amplitudes in both PV and PP decays of J/ψ, measured as the interior angle δ of the triangle representing the amplitudes, is large

$$\delta(J/\psi, \psi(2S))_{PP} = \cos^{-1}\left(\frac{B(K^+K^-) - B(K_SK_L) - \rho B(\pi^+\pi^-)}{2\sqrt{B(K_SK_L) \times \rho \times B(\pi^+\pi^-)}}\right),$$



where ρ = phase space factor

$$\delta(J/\psi)_{PP} = 89.6^\circ \pm 9.9^\circ(\text{Suzuki}),\ 89^\circ \pm 10^\circ(\text{Rosner}),\ 82^\circ \pm 9^\circ(\text{PDG2010})$$

Suzuki [24] raised the natural question if the $\sim \pi/2$ phase difference would also be found in the PP decays of $\psi(2S)$. If not, he wondered if it could perhaps explain the so called $\rho\pi$ (PV) problem: $\mathcal{B}(\psi(2S) \to \rho^0\pi^0)/\mathcal{B}(J/\psi \to \rho^0\pi^0) \approx 0.6\%$, instead of the pQCD expected value of $\sim 13\%$.

Previous measurements with small statistics $\psi(2S)$ data indicated large phase difference, $\delta(\psi(2S))_{PP}$, but with large errors, mainly due to the very small $\mathcal{B}(\psi(2S) \to \pi^+\pi^-)$, whose strong decay is forbidden by isospin conservation.

CLEO has now made a new measurement with 24.5 million $\psi(2S)$, and I present the preliminary results here [25]. The event distributions obtained for the three decays $\psi(2S) \to \pi^+\pi^-, K^+K^-$ and K_SK_L are shown in Fig. 6. The preliminary results for the measured branching fractions for the decays are listed in Table 4. These lead to a more precise result, $\delta(\psi(2S))_{PP} = 114^\circ \pm 11^\circ$.

In summary, both J/ψ and $\psi(2S)$ decays to pseudoscalar pairs give large phase difference between strong and EM amplitudes. The difference between $\delta(J/\psi) = 82^\circ \pm 9^\circ$ and $\delta(\psi(2S)) = 114^\circ \pm 11^\circ$ is 2.3σ. Question: Is this significant?

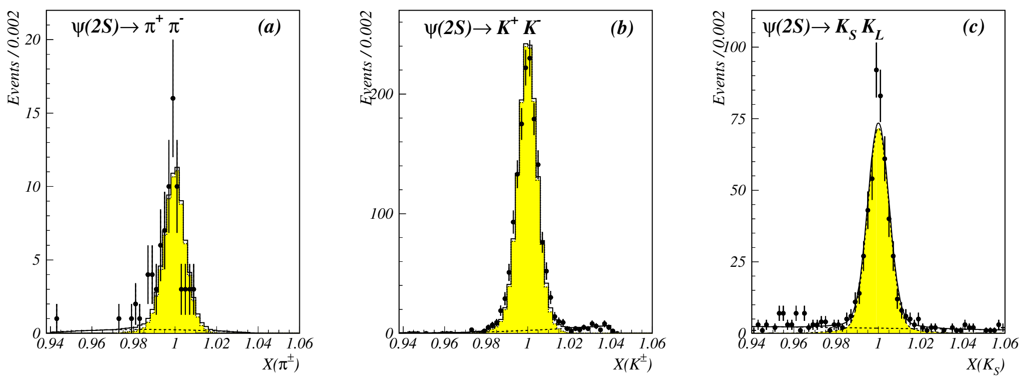


Figure 6: Event distributions as functions of $X(h) \equiv E(h)/E(\text{beam})$ for $h = \pi^{\pm}, K^{\pm}$, and K_S.

	DASP 1979	BES 2004	CLEO 2005	This analysis
$\mathcal{B}(\pi^+\pi^-) \times 10^5$	8 ± 5	0.84 ± 0.65	0.8 ± 0.8	0.72 ± 0.24
$\mathcal{B}(K^+K^-) \times 10^5$	10 ± 7	6.1 ± 2.1	6.3 ± 0.7	7.49 ± 0.43
$\mathcal{B}(K_S K_L) \times 10^5$	–	5.24 ± 0.67	5.8 ± 0.9	5.31 ± 0.43
$\delta(\psi(2S))_{PP}$	–	$(91 \pm 35)^{\circ *}$	$(87 \pm 20)^{\circ *}$	$(114 \pm 11)^{\circ}$

* Recalculated

Table 4: Branching fractions determined for $\psi(2S)$ decays into pseudoscalar pairs, $\pi^+\pi^-, K^+K^-$ and $K_S K_L$, and the resulting interference angle $\delta(\psi(2S))_{PP}$.

9 Summary

We have reported new results from the analysis of CLEO data for $\psi(2S)$, $\psi(4170)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. These include:

1. Branching fractions for $\psi(2S) \to \pi^0 h_c(^1P_1)$.

2. Production of $h_c(^1P_1)$ in $e^+e^-(4170) \to \pi^+\pi^- h_c(^1P_1)$.

3. Branching fractions for $\Upsilon(3S) \to \gamma\chi_{b1.b2}(1P)$.

4. Decays of $\psi(2S)$ and $J/\psi \to p\overline{p} + \gamma$, π^0, and η, and search for $p\overline{p}$ threshold enhancements.

5. Multipole admixtures in $\psi(2S) \to \gamma\chi_J, \chi_J \to \gamma J/\psi$ dipole transitions.

6. Interference between strong and electromagnetic amplitudes in $\psi(2S)$ decays to pseudoscalar pairs, $\pi^+\pi^-$, K^+K^- and $K_S K_L$.

These results pose several interesting physics questions. Among these are:

- Why $\Delta M_{\rm hf}(1P) \equiv \langle M(^3P_J)\rangle - M(^1P_1) = 0$, if $\langle M(^3P_J)\rangle \neq M(^3P)$?
- What hadronic decays account for $\mathcal{B}(h_c \to \text{hadrons}) \approx 50\%$?
- Why is the $p\overline{p}$ threshold enhancement seen in J/ψ decay not seen in $\psi(2S)$ decay?
- What is the significance of the 2.3σ difference seen in the interference angle between strong and electromagnetic PP decays of J/ψ and $\psi(2S)$.

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