HEAVY QUARKONIA
Recent Results from CLEO

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The CLEO experiment at the Cornell Electron Storage Ring (CESR) stopped taking data before Hadron 2009. However, as is well known CLEO had accumulated a large amount of data both in the charmonium and bottomonium energy regions.

Charmonium region	**Bottomonium region**
$\psi(2S, 3686)$: 54 $\text{pb}^{-1}, \sim 27$ million $\psi(2S)$	$\Upsilon(1S)$: 1056 pb^{-1}, 20.8 million $\Upsilon(1S)$
$\psi(3770)$: 818 $\text{pb}^{-1}, \sim 5$ million $\psi(3770)$	$\Upsilon(2S)$: 1305 pb^{-1}, 9.3 million $\Upsilon(2S)$
$\psi(4170)$: 586 $\text{pb}^{-1}, \sim 5$ 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}	

In the past, these data produced a large amount of the physics of open-flavor B mesons, and hidden-flavor bottomonium. With the conversion of CLEO/CESR to CLEO-c/CESR-c in 2003, the charm quark region became accessible to the collaboration, and a number of important discoveries in charmonium and D-physics have been made by CLEO. I am going to talk about only the most recent and exciting of these in strong interaction physics from the spectroscopy of charmonium and bottomonium.

At HADRON 2009 Amiran Tomaradze highlighted the recent achievements of CLEO. These consisted of

- Discovery of $h_c(^1P_1)$ and precision measurement of the hyperfine splitting $\Delta M_{hf}(1P)_{c\bar{c}}$ [PRL 101, 182003 (2008)].
- Confirmation of $\eta_b(1S)$ identification in $\Upsilon(3S) \to \gamma\eta_b(1S)$, since published [PRD 81, 031104(R) (2010)].
- Search for multi pion decays of $h_c(^1P_1)$ [PRD 80, 051106 (2009)].
- First observation of $J/\psi \to 3\gamma$ [PRL 101, 101801 (2008)].
- First measurements of hadronic decays of $\chi_{bJ}(1P, 2P)$ [PRD 78, 091103(R) (2008)].

Since then CLEO has published nearly a dozen papers on the spectroscopy of heavy quarkonia, and many more are in the pipeline.

In these 20 minutes I will describe an admittedly subjective selection from these.

Spin-Singlet States and Hyperfine Interaction

Our interest at CLEO in the study of hyperfine interaction in quarkonia continues.

P-wave Spin-singlet State of Charmonium, $\mathbf{h_c(^1P_1)}$

As stated earlier, we made the first firm identification of $h_c(^1P_1)$ and made a precision measurement of its mass to obtain hyperfine splitting of

$$\Delta M_{hf}(1P)_{c\bar{c}} = \langle M(^3P_J)\rangle - M(^1P_1) = 0.02 \pm 0.23 \text{ MeV}$$ [PRL 101, 182003 (2008)]

It is extremely gratifying that BES III, analyzing about four times larger data set obtains result remarkably identical to ours,

$$\Delta M_{hf}(1P)_{c\bar{c}} = \langle M(^3P_J)\rangle - M(^1P_1) = -0.10 \pm 0.22 \text{ MeV}$$ [PRL 104, 132002 (2010)]

The mystery remains about why this experimental result, based on the invalid identification of $\langle M(^3P_J)\rangle$ with $M(^3P_J)$, is in such perfect agreement with the pQCD prediction of ΔM_{hf}(p-wave)$= 0$.

h_c Beyond Discovery

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 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, we were successful in identifying h_c. Our result is in excellent agreement with the BES III result

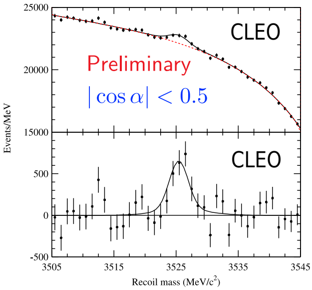
$$\mathcal{B}[\psi(2S) \to \pi^0 h_c] = (9.0 \pm 1.5 \pm 1.2) \times 10^{-4}$$

CLEO

$$= (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$$

BESIII

(PRL 104, 132002 (2010))



New CLEO measurements about $\mathbf{h_c(^1P_1)}$

Hadronic decays of $h_c(^1P_1)$. [PRD80, 051106(R) (2009)]

The $J^{PC} = 1^{+-}$ state h_c radiatively decays to $\eta_c(^1S_0)$ with a branching fraction, $\mathcal{B}(h_c \to \gamma\eta_c) = (54.3 \pm 8.5)\%$[BES III]. The remaining decays must be to hadrons with overall negative C-parity. We have searched for odd pion decays of h_c,

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

No significant yield is found in 3 or 7 pion final states, and only a small 5 pion transition is observed with

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

Interesting question — what are the remaining 45% hadronic decays?

New mode of $h_c(^1P_1)$ production. [arXiv: 1104.2025[hep-ex], submitted to PRL]

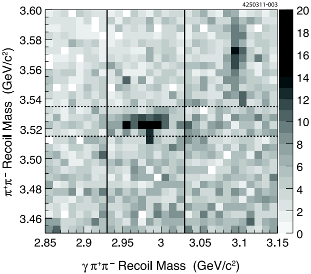
As successful as the observation of $h_c(^1P_1)$ was in its formation in $\psi(2S) \to \pi^0 h_c$, CLEO has discovered a prolific new source of h_c. In the analysis of our data for 586 pb^{-1} of e^+e^- annihilation at $\sqrt{s} = 4170$ MeV we observe a 10σ signal for h_c in the decay

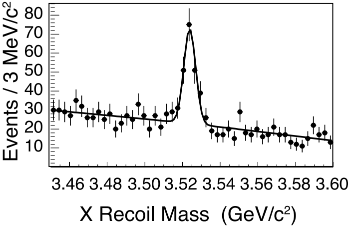
$$e^+e^-(4170) \to \pi^+\pi^- h_c(1P),$$

with $h_c \to \gamma\eta_c, \eta_c \to$ 12 decay modes*.

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

In the two dimensional plot the h_c signal is clearly seen in $\pi^+\pi^-$ recoil mass at the intersection of its radiative decay to η_c. (The enhancement at 3.1 GeV is due to J/ψ.) In the projection it is seen as a strong enhancement over a featureless background. The production cross section is a very healthy 15.6 ± 4.2 pb. A paper has been submitted to PRL for publication. (arXiv:1104.2025[hep-ex])





- Our discovery of the population of $h_c(1P)$ in e^+e^- annihilations above the $D\bar{D}$ 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. (arXiv: 1103.3419 [hep-ex])

Decays of bottomonium p-wave states, $\chi_{bJ}(1P_J)$

Compared to charmonium very few decays of bottomonium states have ever been measured.

Earlier CLEO had made the first measurements of $\chi_{bJ}(1P, 2P)$ decays to 14 exclusive light hadron final state. [PRD78, 091103(R)(2008)]

We have now made measurements of radiative transitions to $\chi_{bJ}(1P)$ states from $\Upsilon(2S)$ and $\Upsilon(3S)$. [PRD83, 054003(2011)]

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

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

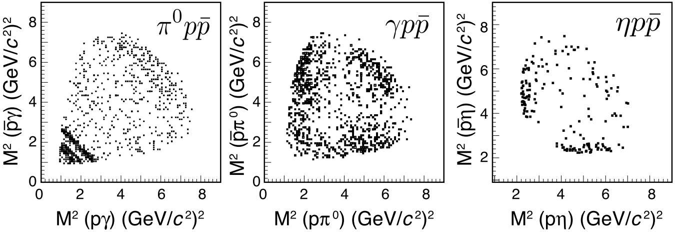
$$\mathcal{B}[\Upsilon(3S) \to \gamma\chi_{b2}(1P)] = (7.7 \pm 1.3) \times 10^{-3} \text{ (CLEO)}, \; < 20.3 \times 10^{-3} \text{ (PDG)}$$

Decays of $\psi(2S)$ to $p\bar{p} + \gamma, \pi^0$ and η, and search for baryonium in $\psi(2S)$ and J/ψ decays [PRD82, 092002(2010)]

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

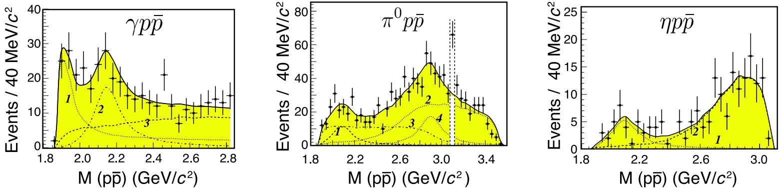
$$\mathcal{B}(J/\psi \to \gamma R_{thr}) \times \mathcal{B}(R_{thr} \to p\bar{p}) = (7.0^{+1.9}_{-0.9}) \times 10^{-5}.$$

- 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 $\eta(p\bar{p})$.
- A detailed analysis of our data set of 24.5 million $\psi(2S)$ was done. Dalitz plots showed that a number of light quark resonances were excited in all three decays.



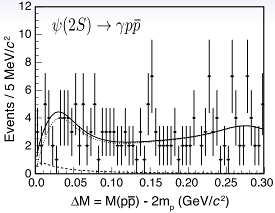
The structures observed in the Dalitz plots were analyzed via their projections, and product branching fractions were determined for a number of baryon (N^*), and meson resonances (R) which decay into $p\bar{p}$. Most of these represent first such measurements.

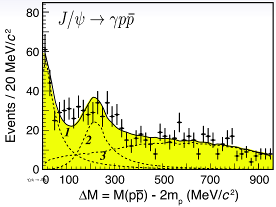
Note: These include observations of $f_2(2150)$ and $N^*(2300)$ before BES III observations of the same.



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	

About $p\bar{p}$ Baryonium





$\boldsymbol{\psi(2S) \to \gamma p\bar{p}}$: We find no evidence for a threshold enhancement in $M(p\bar{p})$.

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

$\boldsymbol{J/\psi \to \gamma p\bar{p}}$: 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 $J/\psi \to \gamma(p\bar{p})$. The fit to the observed enhancement at threshold in the region, $\Delta M = M(p\bar{p} - 2m_p) = 0 - 900$ MeV leads to

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

$$\mathcal{B}(J/\psi \to \gamma \mathrm{R_{thr}}) \times \mathcal{B}(\mathrm{R_{thr}} \to p\bar{p}) = (11.4^{+6.0}_{-4.0}) \times 10^{-5}$$ (PRD 82, 092002 (2010))

BES III has recently confirmed 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 $p\bar{p}$ above threshold, and account for the observed enhancement. BES II and we had earlier proposed this possibility, but BES III makes no comment about it in their paper (PRL 106, 072002(2011)).

Decays of χ_{cJ} to $p\bar{p} + \pi^0, \eta$ and ω [PRD 82, 011103(R) (2010)]

The χ_{cJ} states are strongly populated by the E1 radiative decays of $\psi(2S)$. CLEO has recently made measurements of χ_{cJ} decays to $p\bar{p} + \pi^0, \eta, \omega$, with improved results.

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

Both sets of measurements,

$$\psi(2S) \to p\bar{p} + \gamma, \pi^0, \eta \text{ and } \chi_{cJ} \to p\bar{p} + \pi^0, \eta, \omega$$

are potentially of great value to the future $p\bar{p}$ experimentation at PANDA(GSI).

Multipole Admixtures in Dipole Transitions

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 $a_2 = M2/\sqrt{E_1^2 + M_2^2}$, and

$a_2(\chi_1) = -(E_\gamma/4m_c)(1+\kappa_c)$, 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 were unsuccessful.
CLEO has recently made a high statistics measurement [PRD 80, 112003 (2009)].
$a_2(\chi_{c1}) = (-6.26 \pm 0.67) \times 10^{-2}$, and $a_2(\chi_{c2}) = (-9.3 \pm 1.6) \times 10^{-2}$.

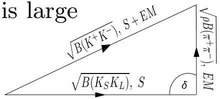
The ratio, $\mathbf{a_2(\chi_{c2})/a_2(\chi_{c1}) = 1.49 \pm 0.30}$ is consistent with $3/\sqrt{5} = 1.34$, justifying the hypothesis of a **single quark transition**.

For assumed $m_c = 1.5$ GeV,
χ_{c1} : $\mathbf{(1+\kappa_c) = 0.88 \pm 0.20}$, χ_{c2} : $\mathbf{(1+\kappa_c) = 1.10 \pm 0.19}$, i.e.,
anomalous magnetic moment of the charm quark, $\boldsymbol{\kappa_c = 0}$.

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 measured [PRD 79, 094504 (2009)].

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

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 and Rosner 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, is large

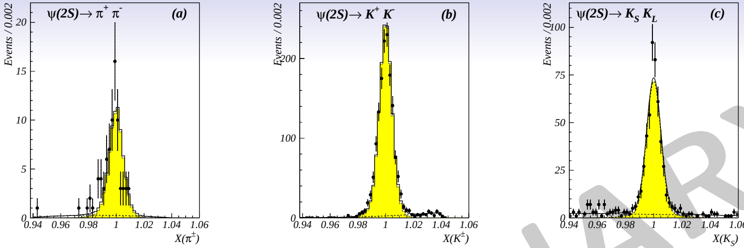


$$\delta(J/\psi, \psi(2S))_{PP} = \cos^{-1}\left(\frac{B(K^+K^-) - B(K_SK_L) - \rho B(\pi^+\pi^-)}{2\sqrt{B(K_SK_L) \times \rho \times B(\pi^+\pi^-)}}\right)$$

ρ = phase space factor

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

- It was natural to ask if the $\sim \pi/2$ phase difference would also be found in the PP decays of $\psi(2S)$. If not, Suzuki wondered if it could perhaps explain the so called $\rho\pi$ (PV) problem.
- 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 $\psi(2S)$ with a more precise result, $\delta(\psi(2S))_{PP} = 114^\circ \pm 11^\circ$.

	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

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

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 $J/\psi \to p\bar{p} + \gamma$, π^0, and η, and search for $p\bar{p}$ 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 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 $\mathcal{B}(h_c \to \text{hadrons}) \approx 45\%$?
- Why is the $p\bar{p}$ 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 $\psi(2S)$.