Charmonium spectroscopy and decay at CLEO-c*

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Abstract We report recent results on charmonium spectroscopy and decay from the CLEO-c experiment at the Cornell electron-positron storage ring accelerator, CESR. Most of the results are based on the analysis of 54 pb^{-1} of luminosity collected at the $\psi(2S)$ resonance, corresponding to 27 M $\psi(2S)$ decays. We concentrate on radiative decays of $\psi(2S)$ and J/ψ, on two-body mesonic decay of χ_{cJ}, on hadronic decay of the h_c, and on higher multipoles in the two-photon cascade $\psi(2S)\to\gamma\chi_{cJ}$, $\chi_{cJ}\to\gamma J/\psi$.

Key words charmonium, radiative decay, two-body decay, photon transitions, higher multipoles

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1 Introduction

The CLEO-c experiment at the Cornell electron-positron storage ring accelerator, CESR, collected 54 pb^{-1} of luminosity at the $\psi(2S)$, corresponding to approximately 27 M $\psi(2S)$ decays. The experiment finished data taking in March of 2008, completing an extensive, multi-year program to study open charm (see the contributions by R. Briere and P. Zweber to this conference) as well as charmonium. The $\psi(2S)$ data sample collected, apart from being a source of direct decays also serves as a "factory" of tagged charmonium bound states such as $\chi_{cJ}(J=2,1,0)$ and h_c, the singlet states η_c and η_c', as well as the J/ψ itself via the dipion transition, $\psi(2S)\to\pi\pi J/\psi$. This makes the twis an ideal laboratory to test quarkonium potential models and many variants of QCD (NRQCD, pQCD, LQCD). The present talk will give recent highlights from such studies.

2 Two-body mesonic decays of χ_{cJ}

Two-body decays of χ_{cJ} are theoretically "clean"; they probe the gluon content of the final-state mesons and the role of the color-octet mechanism. We have studied the pseudoscalar final states, $\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, K_sK_s, $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$. We observe significant signals signals from both χ_{c0} and χ_{c2} in nearly all final states investigated. (The decay of χ_{c1} to two pseudoscalars is forbidden by parity conservation.) Fig. 1 shows the branching fractions (BF) and upper limits (UL, respectively, compared with the previous PDG values. Our measurements constitute substantial improvements over current world averages in some channels.

Mode		χ_{c0}	χ_{c2}
$\pi^+\pi^-$	This Work	$6.37\pm0.08\pm0.29\pm0.32$	$1.59\pm0.04\pm0.07\pm0.10$
	PDG [5]	4.87 ± 0.40	1.42 ± 0.16
$\pi^0\pi^0$	This Work	$2.94\pm0.07\pm0.32\pm0.15$	$0.68\pm0.03\pm0.07\pm0.04$
	PDG	$2.43\pm.20$	0.71 ± 0.08
K^+K^-	This Work	$6.47\pm0.08\pm0.33\pm0.32$	$1.13\pm0.03\pm0.06\pm0.07$
	PDG	5.5 ± 0.6	0.78 ± 0.14
$K^0_SK^0_S$	This Work	$3.49\pm0.08\pm0.17\pm0.17$	$0.53\pm0.03\pm0.03\pm0.03$
	PDG	2.77 ± 0.34	0.68 ± 0.11
$\eta\eta$	This Work	$3.18\pm0.13\pm0.31\pm0.16$	$0.51\pm0.05\pm0.05\pm0.03$
	PDG	2.4 ± 0.4	<0.5
$\eta\eta'$	This Work	<0.25	<0.06
		$(0.16\pm0.06\pm0.01\pm0.01)$	$(0.013\pm0.031\pm0.001\pm0.001)$
	PDG	<0.5	<0.26
$\eta'\eta'$	This Work	$2.12\pm0.13\pm0.18\pm0.11$	<0.10
			$(0.056\pm0.032\pm0.005\pm0.003)$
	PDG	1.7 ± 0.4	<0.4

Fig. 1. CLEO measurements of χ_{cJ} branching fractions or 90% CL upper limits (in units of 10^{-3}) to two pseudoscalar mesons.

The results have been published in Ref. [1]. We also note that CLEO results on two-body baryonic decays of χ_{cJ} have recently been published [2]. Our results on the $\eta(')\eta(')$ final states constrain the ratio of double-OZI (DOZI) to single-OZI (SOZI) amplitudes [3], as shown in Fig. 2. The data suggest that

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the DOZI contribution to the decays in the 0^+ channel is at most very small.

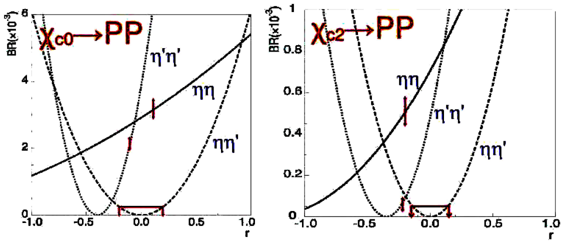

Fig. 2. CLEO measurements (vertical bars) of $\eta(')\eta(')$ branching fractions from χ_{c0} and χ_{c2}, compared to predictions [3] as a function of the ratio, r, of DOZI to SOZI amplitudes (curves).

3 Hadronic decay of the h_c

The only previously observed decay of the h_c was in the "discovery" channel, $\psi(2S)\to\pi^0 h_c$, $h_c\to\gamma\eta_c$, with a product branching fraction of $4.2\pm0.6)\times10^{-4}$ [4]. Godfrey and Rosner [5] predict 56.8% of h_c decays to be direct hadronic. To guide our event selection we expect a substantial fraction of hadronic final states to be an odd number of pions, in analogy to the J/ψ because of its negative G parity. We observe a significant signal in the final state $2(\pi^+\pi^-)\pi^0$ with a product BF of $(1.9\pm0.5\pm0.4)\times10^{-5}$. This consitutes the first observed hadronic decay of the h_c. As a byproduct we obtain upper limits on the product BF's for the final states $\pi^+\pi^-\pi^0$ and $3(\pi^+\pi^-)\pi^0$ of 0.2×10^{-5} and 2.4×10^{-5}, respectively. This result has been published in [6].

4 $B(\psi(2S)\to\gamma gg)/B(\psi(2S)\to ggg)$

We have studied the incusive photon spectrum in $\psi(2S)$ decay, to measure the branching fraction of $\psi(2S)\to\gamma gg$. While measuring the photon spectrum is straightforward the experimental challenge lies in identifying and subtracting the backgrounds which turn out to be the dominant source of systematic error. To this end we utilize three separate techniques using data, MC, and the "pseudo photon" method described in [7]. From the measured photon spectrum we subtract all other known decays and transitions (amounting to 87% of the total) to infer the amount of $\psi(2S)\to ggg$. We obtain [8] $B(c\bar{c}\to\gamma gg)/B(c\bar{c}\to ggg)=0.091\pm0.003\pm0.027$ for $\psi(2S)$, to be compared with $0.137\pm0.001\pm0.016$ for J/ψ [7], and $0.027\pm0.001\pm0.003$, $0.032\pm0.001\pm0.005$, and $0.027\pm0.001\pm0.005$ for $\Upsilon(1S,2S,3S)$, respectively [9]. This measurement completes the systematic study of inclusive photon spectra at CLEO for all heavy quarkonia bound states.

5 $J/\psi,\psi(2S)\to\gamma\eta_c$

Measuring the BF of $J/\psi\to\gamma\ \eta_c$ via identifying the transition photon in the inclusive photon spectrum from J/ψ is not feasible in CLEO. The reason is the combination of high background and insufficient calorimeter resolution for photon energies in the 50–150 MeV energy range. Instead, we extract the information from separate "auxiliary" measurements in both of which we observe clean signals, (A) the inclusive photon spectrum from $\psi(2S)$, yielding $B(\psi(2S)\to\gamma\eta_c=(4.32\pm0.16\pm0.60)\times10^{-3}$, and (B) the ratio, $B(J/\psi\to\gamma\ \eta_c)/B(\psi(2S)\to\gamma\eta_c)$ from exclusive η_c decays in both channels. By multiplying (A) with (B) we obtain [11] the desired BF for which we measure $B(J/\psi\to\gamma\ \eta_c)=(1.98\pm0.09\pm0.30)\%$. This is in good agreement with recent lattice QCD results [10] which predict $\Gamma_{\gamma\eta_c}=(2.0\pm0.1\pm0.4)$ keV, corresponding to $B(J/\psi\to\gamma\ \eta_c)=(2.1\pm0.1\pm0.4)\%$.

One surprise encountered in this analysis was the non-trivial lineshape of the η_c and the sensitivity of the result to the modeling of it. Understanding the energy dependence of the J/ψ, $\psi(2S)\to\gamma\eta_c$ matrix elements [12] is crucial for an accurate mass measurement from radiative decays. The η_c mass uncertainty in turn drives the experimental error on the $1S$ hyperfine splitting in charmonium.

6 Search for $\psi(2S)\to\gamma\eta_c'$

The transition photon in this process is expected to have an energy of 48 MeV, again too low for inclusive study. We instead search for the exclusive cascades, $\psi(2S)\to\gamma\eta_c'$, $\eta_c'\to X$, and $\psi(2S)\to\gamma\eta_c'$, $\eta_c'\to\pi^+\pi^-\eta_c$, $\eta_c\to X$. We use the known values for $B(\eta_c'\to KK\pi)$ and several decay channels of the η_c for which branching fractions are known. We do not observe signals in any of the channels studied and set 90% CL upper limits [13]: $B(\psi(2S)\to\gamma\ \eta_c')<7.4\times10^{-4}$, $B(\psi(2S)\to\gamma\ \eta_c')\times B(\eta_c'\to\pi^+\pi^-\eta_c)<1.4\times10^{-4}$. We note that this result is consistent with the value, $B(\psi(2S)\to\gamma\ \eta_c')\approx4\times10^{-4}$, expected by scaling from $J/\psi\to\gamma\ \eta_c$.

7 $J/\psi,\psi(2S)\to\gamma(\pi^0,\eta,\eta')$

We have studied radiative decays of charmonium into pseudoscalar final states and obtain [14] the results shown in Fig. 3. A quantity of great interest in this context is the ratio, $R_n := \frac{B(\psi(nS)\to\gamma\eta)}{B(\psi(nS)\to\gamma\eta')}$. We find $R_1 = (21.1\pm0.9)\%$ which is consistent with known $\eta-\eta'$ mixing. For R_2, however, which is expected to be approximately equal to R_1, we find the surprisingly low upper limit, $R_2 < 1.8\%$ at 90% CL. Such suppression of $\gamma\eta$ decays of the $\psi(2S)$ is entirely unexpected and may indicate yet undiscovered features in the nature of the $\psi(2S)$.

Mode	This result (10^{-4})
$J/\psi \to \gamma\pi^0$	$0.363 \pm 0.036 \pm 0.013$
$\to \gamma\eta$	$11.01 \pm 0.29 \pm 0.22$
$\to \gamma\eta'$	$52.4 \pm 1.2 \pm 1.1$
$\psi(2S) \to \gamma\pi^0$	< 0.07
$\to \gamma\eta$	< 0.02
$\to \gamma\eta'$	$1.19 \pm 0.08 \pm 0.03$

Fig. 3. CLEO measurements of branching fractions of radiative decay of J/ψ and $\psi(2S)$ to pseudoscalars.

8 $\chi_{cJ} \to \gamma(\rho, \omega, \phi)$

These processes are of theoretical interest in that their decay diagrams are analogous to those of glueball production, e.g. in $J/\psi \to \gamma f_J$. We select events of the type, $\psi(2S) \to \gamma_{(\rm low)}\chi_{cJ}$, $\chi_{cJ} \to \gamma_{(\rm high)}(\rho,\omega,\phi)$. The results [15] are shown in Fig. 4. We observe significant signals in $\chi_{c1}\to\gamma\rho$ and in $\chi_{c1}\to\gamma\omega$, at rates an order of magnitude higher than predicted [16] by pQCD.

Mode	$\mathcal{B}\times 10^6$	U.L. $[10^{-6}]$	pQCD $[10^{-6}]$
$\chi_{c0} \to \gamma\rho^0$		< 9.6	1.2
$\chi_{c1} \to \gamma\rho^0$	$243 \pm 19 \pm 22$		14
$\chi_{c2} \to \gamma\rho^0$	$25 \pm 10^{+8}_{-14}$	< 50	4.4
$\chi_{c0} \to \gamma\omega$		< 8.8	0.13
$\chi_{c1} \to \gamma\omega$	$83 \pm 15 \pm 12$		1.6
$\chi_{c2} \to \gamma\omega$		< 7.0	0.50
$\chi_{c0} \to \gamma\phi$		< 6.4	0.46
$\chi_{c1} \to \gamma\phi$	$12.8 \pm 7.6 \pm 1.5$	< 26	3.6
$\chi_{c2} \to \gamma\phi$		< 13	1.1

Fig. 4. CLEO measurements of branching fractions of radiative decay of χ_{cJ} to vector mesons.

9 $\chi_{cJ} \to \gamma\gamma$

The two-photon widths of the χ_{cJ} states probe relativistic and radiative corrections which are known to be significant in charmonium. While the two-photon widths of the $J = 0$ and $J = 2$ states have been measured previously and with comparable precision, we report here a measurement of both in the same experiment via the cascade decay, $\psi(2S)\to\gamma\chi_{cJ}$, $\chi_{cJ}\to\gamma\gamma$. We obtain [17], $\Gamma_{\gamma\gamma}(\chi_{c2}) = (0.66\pm0.07_{\rm stat}\pm0.04_{\rm sys}\pm0.05_{PDG})$ keV and $\Gamma_{\gamma\gamma}(\chi_{c0}) = (2.36\pm0.07_{\rm stat}\pm0.04_{\rm sys}\pm0.05_{PDG})$ keV. Of particular interest is the ratio, $R := \frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c0})}$, for which we find $R = 0.278\pm0.050_{\rm stat}\pm0.018_{\rm sys}\pm0.031_{\rm PDG}$, resulting in a new world average, $R = 0.22 \pm 0.03$. This is to be compared with the prediction from pQCD where in the ratio of the widths the uncertainties due to quark mass and wave function at the origin cancel. To first order in α_s we expect $R = (4/15)[1 - 1.76\alpha_s]$ which, assuming $\alpha_s = 0.32$ would give $R = 0.12$. Evidently, higher-order corrections are significant.

10 $J/\psi \to 3\gamma$

This process is the quarkonium analogue of ortho-positronium decay. No three-photon decay of any meson had been observed before. We tag the decay via $\psi(2S)\to\pi^+\pi^- J/\psi$ which eliminates QED backgrounds. We veto the known resonances, π^0, η, η' and η_c, leaving as the dominant background $J/\psi\to\gamma\pi^0\pi^0$ where two of the five photons merge with other photons or escape undetected. We then perform a kinematic fit. The resulting distribution of χ^2/dof (see Fig. 5) cleanly separates the signal (which peaks near zero) from the background (which rises away from zero and turns out to be independent of resonant $\pi^0\pi^0$ substructure).

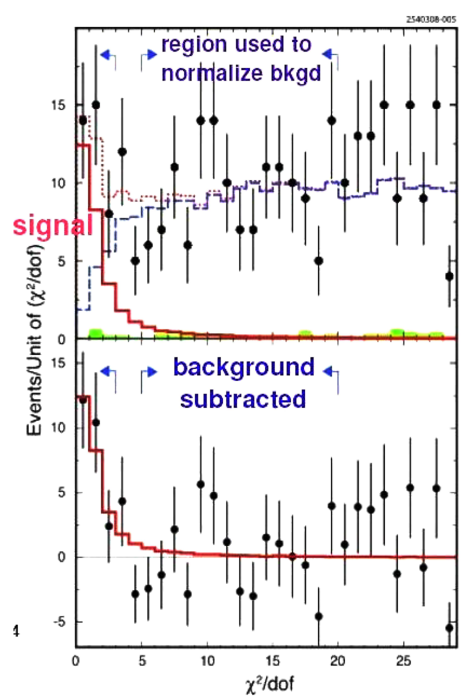

Fig. 5. Distribution of χ^2/dof after kinematic fit for events selected in the analysis of $J/\psi\to 3\gamma$.

We find a signal of 6σ significance and obtain $B(\mathrm{J}/\psi\rightarrow 3\gamma) = (1.2\pm0.3\pm0.2)\times10^{-5}$. This constitutes the first observed 3γ decay of any meson. Comparing this result to theory, we note that it is roughly consistent with lowest-order expectations, e.g. $B(3\gamma)/B(3\mathrm{g})\approx(\alpha/\alpha_s)^3$ or $B(3\gamma)\approx(\alpha/14)B_{\mu\mu}\approx 3\times10^{-5}$, but that NLO QCD corrections give a negative rate! Evidently, higher-order corrections are very significant.

As a byproduct of this analysis we obtain a 90% CL upper limit on $B(\eta_c\rightarrow\gamma\gamma)<3\times10^{-4}$, to be compared with the PDG value of $(2.7\pm0.9)\times10^{-4}$.

11 Higher multipoles in radiative transitions

While it is well-known that the photon transitions, $\psi(2S)\rightarrow\gamma\chi_{cJ}\rightarrow\gamma\gamma\ \mathrm{J}/\psi$ in charmonium are dominantly electric dipole (E1), higher multipoles are allowed: M2 for $J=1$, M2 and E3 for $J=2$ (although no E3 for a S $\rightarrow$ P single-quark transition). The M2 transition also measures the total magnetic moment of the charm quark. There has been a long-standing discrepancy between theory and previous experiments, as well as between different experiments.

We studied the angular distributions of the photons in the above decay chains as they are sensitive to higher multipoles. We select events in which the final-state J/ψ decays into a lepton pair (e^+e^- or $\mu^+\mu^-$) which allows reconstruction of the complete process starting with the initial incoming e^+e^- pair of the CESR beam. For clarity of notation, in this section we denote $\psi(2S)$ by ψ'. We define the following quantities. "Primed" angles (θ',ϕ'): initial lepton pair orientation relative to γ' in $\psi'\rightarrow\gamma'\chi_{cJ}$, "unprimed" angles (θ,ϕ): final lepton pair orientation relative to γ in $\chi_{cJ}\rightarrow\gamma\mathrm{J}/\psi$, and $\theta_{\gamma\gamma'}$: angle between γ and γ' in the χ_{cJ} rest frame. The combined angular distribution, $W(\cos\theta',\phi',\cos\theta_{\gamma\gamma'},\cos\theta,\phi)$ then depends on multipole amplitudes $a^{J_\chi}_{J_\gamma}$ (see Ref. [19]). Fig. 6 shows the projection of our measured W distribution onto $|\cos\theta|$ for both $J_\chi=1$ and $J_\chi=2$, demonstrating the deviation of the data from pure E1 expectation. We obtain a good fit assuming (i) $m_c=1.5\ \mathrm{GeV}/c^2$, (ii) no electric quadrupole (E3) contribution, and (iii) no anomalous quark magnetic moment. Fig. 7 shows the fitted M2 amplitudes a_2, b_2 extracted from the data, compared with the predictions from pure E1 and from combined E1+M2. We find significant M2 admixtures, at the $>11\sigma$ level for $J=1$ and at the $>6\sigma$ level for $J=2$. Our measured M2 amplitudes are in good agreement with theoretical predictions [19]. This resolves a long-standing discrepancy in the literature, as shown in Fig. 8. The results have been published in Ref. [20].

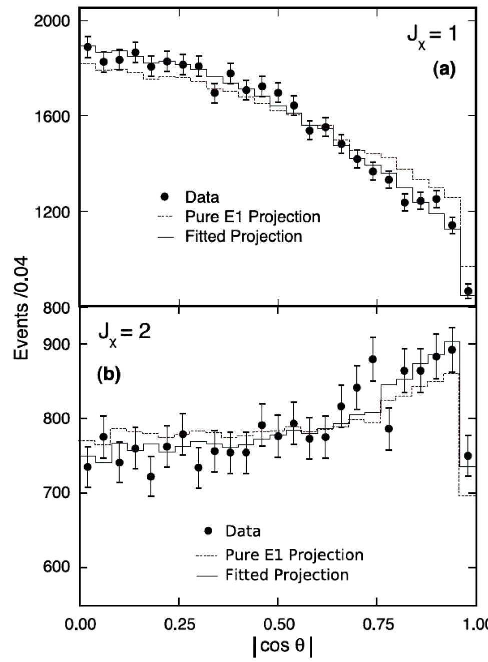

Fig. 6. Angular distribution of photons from the $\psi(2S)\rightarrow\gamma\chi_{cJ}$, $\chi_{cJ}\rightarrow\gamma\mathrm{J}/\psi$ cascade decay.

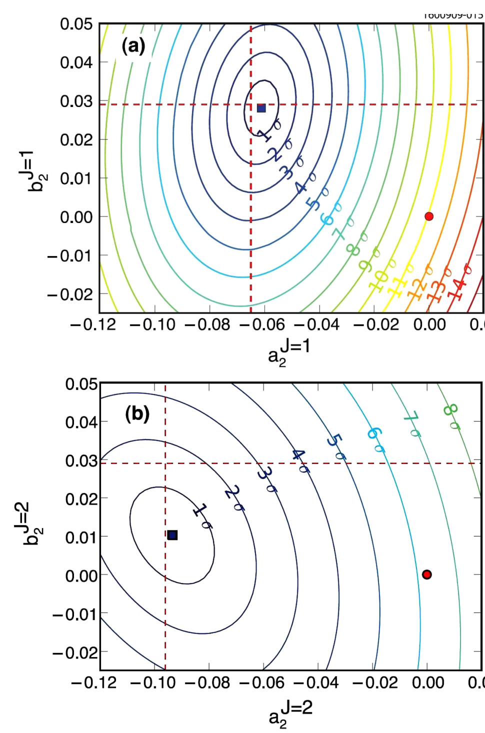

Fig. 7. CLEO results on fitted multipole amplitudes, with error ellipses shown. In each plot, the point at (0,0) indicates the expectation based on the assumption of pure E1, and the intersection of the dashed straight lines is the prediction of combined (E1+M2).

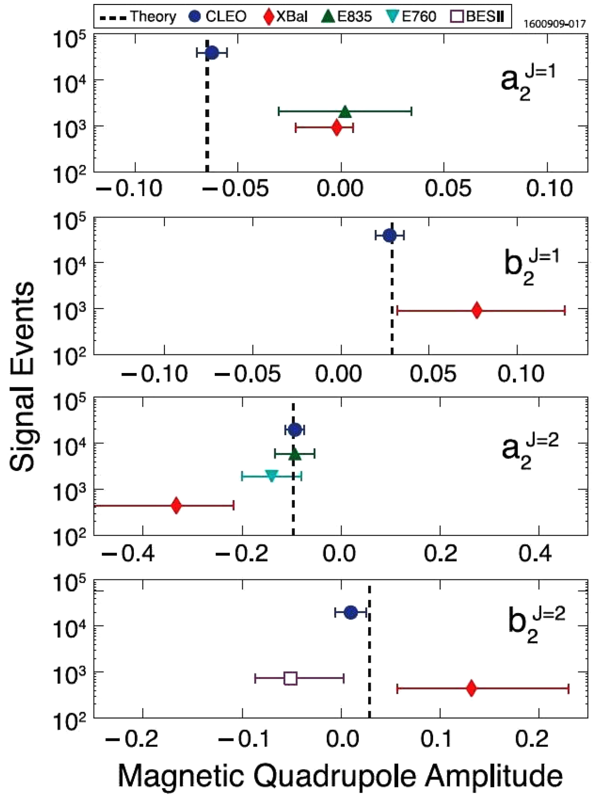

Fig. 8. Comparison of results on M2 amplitudes from different experiments. In each plot the top (blue) data point indicates the recent CLEO-c result, and the vertical dashed line indicates the theoretical prediction. The vertical axis gives the number of signal events on which the respective analyses were based.

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References

1 Asner D M et al (CLEO collaboration). Phys. Rev. D, 2009, **79**: 072007

2 Naik P et al (CLEO collaboration). Phys. Rev. D, 2008, **78**: 031101(R)

3 Close F E, ZHAO Q. Phys. Rev. D, 2005, **71**: 094022; ZHAO Q, Phys. Rev. D, 2005, **72**: 074001

4 Dobbs S et al (CLEO collaboration). Phys. Rev. Lett., 2008, **101**: 182003

5 Godfrey S, Rosner J L. Phys. Rev. D, 2002, **66**: 014012

6 Adams G S et al (CLEO collaboration). Phys. Rev. D, 2009, **80**: 051106(R)

7 Besson D et al (CLEO collaboration). Phys. Rev. D, 2008, **78**: 032012

8 Libby J et al (CLEO collaboration). Phys. Rev. D, 2009, **80**: 072002

9 Besson D et al (CLEO collaboration). Phys. Rev. D, 2006, **74**: 012003

10 Dudek J J, Edwards R G, Richards D G. Phys. Rev. D, 2006, **73**: 074507

11 Mitchell R E et al (CLEO collaboration). Phys. Rev. Lett., 2009, **102**: 011801

12 Brambilla N, Jia Y, Vairo A. Phys. Rev. D, 2006, **73**: 054005

13 Cronin-Hennessy D et al (CLEO collaboration). arXiv:0910.1234, submitted to Phys. Rev. D

14 Pedlar T K et al (CLEO collaboration). Phys. Rev. D, 2009, **79**: 111101(R)

15 Bennett J V et al (CLEO collaboration). Phys. Rev. Lett., 2008, **101**: 151801

16 GAO Y J, ZHANG Y J, CHAO K T. Chin. Phys. Lett., 2006, **23**: 2376

17 Ecklund K M et al (CLEO collaboration). Phys. Rev. D, 2008, **78**: 091501

18 Adams G S et al (CLEO collaboration). Phys. Rev. Lett., 2008, **101**: 101801

19 Karl G, Meshkov S, Rosner J L. Phys. Rev. Lett., 1980, **45**: 215–218; Sebastian K J, Grotch H, Ridener F L. Phys. Rev. D, 1992, **45**: 3163–3172

20 Artuso M et al (CLEO collaboration). Phys. Rev. D, 2009, **80**: 112003