Abstract. New results on hadron spectra have been appearing in abundance in the past few years as a result of improved experimental techniques. These include information on states made of both light quarks (u, d, and s) and with one or more heavy quarks (c, b). The present review, dedicated to the memory of R. H. Dalitz, treats light-quark states, glueballs, hybrids, charmed and beauty particles, charmonium, and $b\bar{b}$ states. Some future directions are mentioned.

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INTRODUCTION

Quantum Chromodynamics (QCD) is our theory of the strong interactions. However, we are far from understanding how it works in many important cases. Many hadrons discovered recently have puzzling properties. Hadron spectra often are crucial in separating electroweak physics from strong-interaction effects. QCD may not be the only instance of important non-perturbative effects; one should be prepared for surprises at the Large Hadron Collider (LHC). Sharpening spectroscopic techniques even may help understand the intricate structure of masses and transitions at the quark and lepton level.

The QCD scale is $\sim 200$ MeV (momentum) or $\sim 1$ fm (distance), where perturbation theory cannot be used. Although lattice gauge theories are the eventual tool of choice for describing effects in this regime, several other methods can provide information, especially for multi-quark and multi-hadron problems not yet feasible with lattice techniques. These include chiral dynamics (treating soft pions, chiral solitons, and possibly parity doubling in spectra [1]), heavy quark symmetry (describing hadrons with one charm or beauty quark as QCD “hydrogen” or “deuterium” atoms), studies of correlations among quarks [2, 3, 4] and new states they imply (such as a weakly decaying $bq\bar{c}q'$ state [2]), potential descriptions (including relativistic and coupled-channel descriptions), and QCD sum rules. I will describe phenomena to which these methods might be applied.

In the present review I treat light-quark (and no-quark) states, charmed and beauty hadrons, and heavy quarkonium ($cc$ and $b\bar{b}$), and conclude with some future prospects.

LIGHT-QUARK STATES

Several issues are of interest these days in light-quark spectroscopy. These include (1) the nature of the low-energy S-wave $\pi\pi$ and $K\pi$ interactions; (2) the proliferation of interesting threshold effects in a variety of reactions, and (3) the interaction of quark and gluonic degrees of freedom.
Low-energy $\pi\pi$ S-wave

An S-wave $\pi\pi$ low-mass correlation in the $I = 0$ channel ("$\sigma$") has been used for many years to describe nuclear forces. Is it a resonance? What is its quark content? What can we learn about it from charm and beauty decays? This particle, otherwise known as $f_0(600)$ [5], can be described as a dynamical $I = J = 0$ resonance in elastic $\pi\pi$ scattering using current algebra, crossing symmetry, and unitarity [6, 7, 8]. It appears as a pole with a large imaginary part with real part at or below $m_\rho$. Its effects differ in $\pi\pi \rightarrow \pi\pi$, where an Adler zero suppresses the low-energy amplitude, and inelastic processes such as $\gamma\gamma \rightarrow \pi\pi$ [9], where the lack of an Adler zero leads to larger contributions at low $m_{\pi\pi}$.

Modern treatments of the low-energy $\pi\pi$ interaction implement crossing symmetry using an elegant set of exact low-energy relations [10]. In one approach [11] a $\sigma$ pole is found at $441 - i272$ MeV, corresponding to a full width at half maximum of 544 MeV; another [12] finds the pole at $555 - i262$ MeV. Such a $\sigma$ provides a good description of $\gamma\gamma \rightarrow \pi^0\pi^0$ [13], as shown in Fig. 1 with $\Gamma(\sigma \rightarrow \gamma\gamma) = (4.1 \pm 0.3)$ keV. While this large partial width might be viewed as favoring a $q\bar{q}$ interpretation of $\sigma$ [13], a $\pi\pi$ dynamical resonance seems equally satisfactory [9]. Other recent manifestations of a $\sigma$ include the decays $D^+ \rightarrow \sigma\pi^+ \rightarrow \pi^+\pi^+\pi^-$ [14] and $J/\psi \rightarrow \omega\sigma \rightarrow \omega\pi^+\pi^-$ [15], where the $\sigma$ pole appears at $(541 \pm 39) - i(252 \pm 42)$ MeV (or $(500 \pm 30) - i(264 \pm 30)$ MeV in an independent analysis [16]). Successful fits without a $\sigma$ have been performed, but have been criticized in Ref. [17].
Low-energy $K\pi$ S-wave

Is there a low-energy $K\pi$ correlation ("κ")? Can it be generated dynamically in the same manner as the $\sigma$? Some insights are provided in [8,18].

The low-energy $K\pi$ interaction in the $I=1/2, J=0$ channel is favorable to dynamical resonance generation: The sign of the scattering length is the same as for the $I=J=0 \pi\pi$ interaction. A broad scalar resonance $\kappa$ is seen in the $I=1/2, J=0 K^-\pi^+$ subsystem in $D^+ \rightarrow K^-\pi^+\pi^+$, and a model-independent phase shift analysis shows resonant $J=0$ behavior in this subsystem [19]. The $\kappa$ is also seen by the BES II Collaboration in $J/\psi \rightarrow \bar{K}^{*0}(892)K^+\pi^-$ decays [20]. An independent analysis of the BES II data [12] finds a $\kappa$ pole at $745-i316$ MeV, while a combined analysis of $D^+ \rightarrow K^-\pi^+\pi^+$, elastic $K\pi$ scattering, and the BES II data [21] finds a pole at $M(\kappa) = (750^{+30}_{-55}) - i(342 \pm 60)$ MeV.

The $\kappa$, like the $\sigma$, is optional in many descriptions of final-state interactions. An example is a recent fit to the $D^0 \rightarrow K^+K^-\pi^0$ Dalitz plot based on CLEO data [22], shown in Fig. 2. The bands correspond to $K^{*-}$ (vertical), $K^{*+}$ (horizontal), and $\phi$ (diagonal). One can see the effect of an S-wave (nonresonant or $\kappa$) background interfering with $K^{*+}$ and $K^{*-}$ with opposite signs on the left and bottom of the plot.

Depopulated regions at $m(K^+\pi^0) \approx 1$ GeV/c$^2$ may be due to the opening of the $K\pi^0 \rightarrow K\eta$ S-wave threshold (a $D^0 \rightarrow K^+K^-\eta$ Dalitz plot would test this) or to a vanishing S-wave $K\pi$ amplitude between the $\kappa$ and a higher $J^P = 0^+$ resonance.
Dips and edges

With the advent of high-statistics Dalitz plots for heavy meson decays one is seeing a number of dips and edges which often are evidence for thresholds [23]. An example is shown in a recent $D^0 \rightarrow K^0\pi^+\pi^-$ plot (Fig. 3) from BaBar [24] (see also results from Belle [25] and CLEO [26]). The vertical band corresponds to $K^{*-}$ and the diagonal to $\rho^0$. The sharp edges along the diagonal in the $\pi^+\pi^-$ spectrum correspond to $\rho^-\omega$ interference [around $M(\pi\pi) = 0.8\text{ GeV}/c^2$] and to $\pi^+\pi^- \leftrightarrow K\bar{K}$ [around $M(\pi\pi) = 1\text{ GeV}/c^2$]. Rapid variation of an amplitude occurs when a new S-wave channel opens because no centrifugal barrier is present.

Further dips are seen in $6\pi$ photoproduction just at $p\bar{p}$ threshold; in $Re^+e^-$ just below the threshold for S-wave production of $D(1865) + D_1(2420)$; and in the Dalitz plot for $B^\pm \rightarrow K^\pm K^\mp K^\pm$ around $M(K^+K^-) = 1.6\text{ GeV}/c^2$ [27], which could be a threshold for vector meson pair production.

Glueballs and hybrids

In QCD, quarkless “glueballs” may be constructed from pure-glue configurations: $F_{\mu\nu}F^{\mu\nu}$ for $J^{PC} = 0^{++}$ states, $F_{\mu\nu}F^{a\mu\nu}$ for $J^{PC} = 0^{-+}$ states, etc., where $F^{a}_{\mu\nu}$ is the gluon field-strength tensor. All such states should be flavor-singlet with isospin $I = 0$, though couplings of spinless states to $s\bar{s}$ could be favored [28]. Lattice QCD calculations predict the lowest glueball to be $0^{++}$ with $M \approx 1.7\text{ GeV}$ [29]. The next-lightest states, $2^{++}$ and $0^{-+}$, are expected to be several hundred MeV/$c^2$ heavier. Thus it is reassuring that the lightest mainly flavor-singlet state, the $\eta'$, is only gluonic ($8 \pm 2\%$) of the time,
as indicated by a recent measurement of $\mathcal{B}(\phi \to \eta'\gamma)$ by the KLOE Collaboration $^{30}$.

Many other $I = 0$ levels, e.g., $q\bar{q}$, $qg\bar{g}$ ($g =$ gluon), $qq\bar{q}g\ldots,$ can mix with glueballs. One must study $I = 0$ levels and their mesonic couplings to separate out glueball, $n\bar{n} \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$, and $s\bar{s}$ components. Understanding the rest of the flavored $q\bar{q}$ spectrum for the same $J^P$ thus is crucial. The best $0^{++}$ glueball candidates (mixing with $n\bar{n}$ and $s\bar{s}$) are at 1370, 1500, and 1700 MeV. One can explore their flavor structure through production and decay, including looking for their $\gamma(\rho, \omega, \phi)$ decays $^{31}$. A CLEO search for such states in $\Upsilon(1S) \to \gamma X$ finds no evidence for them but does see the familiar resonance $f_2(1270)$ $^{32}$.

QCD predicts that in addition to $q\bar{q}$ states there should be $qg\bar{g}$ ("hybrid") states containing a constituent gluon $g$. One signature of them would be states with quantum numbers forbidden for $q\bar{q}$ but allowed for $qg\bar{g}$. For $q\bar{q}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, so $CP = (-1)^{S+1}$. The forbidden $qg\bar{g}$ states are then those with $J^{PC} = 0^{--}$ and $0^{++}$, $1^{--}$, $2^{++}$, $\ldots$. A consensus in quenched lattice QCD is that the lightest exotic hybrids have $J^{PC} = 1^{--}$ and $M(n\bar{q}g) \simeq 1.9$ GeV, $M(s\bar{q}g) \simeq 2.1$ GeV, with errors 0.1–0.2 GeV $^{33}$. (Unquenched QCD must treat mixing with $qq\bar{q}g$ and meson pairs.) Candidates for hybrids include $\pi_1(1400)$ (seen in some $\eta\pi$ final states, e.g., in $pp$ annihilations) and $\pi_1(1600)$ (seen in $3\pi, \rho\pi, \eta'\pi$). Brookhaven experiment E-852 published evidence for a $1^{++}$ state called $\pi_1(1600)$ $^{34}$. A recent analysis by a subset of E-852’s participants $^{35}$ does not require this particle if a $\pi_2(1670)$ contribution [an orbital excitation of the $\pi(140)$] is assumed. The favored decays of a $1^{++}$ hybrid are to a $q\bar{q}(L = 0) + qg\bar{g}(L = 1)$ pair, such as $\pi b_1(1235)$. A detailed review of glueballs and hybrids has been presented by C. Meyer at this Conference $^{36}$.

CHARMED STATES

The present status of the lowest $S$-wave states with a single charmed quark is shown in Fig. 4. We will discuss progress on orbitally-excited charmed baryons $^{37, 38}$ and charmed-strange mesons, with brief remarks on $D^+$ and $D_s^+$ decay constants which are treated in more detail in Ref. $^{39}$.

Charmed $L > 0$ baryons

For many years CLEO was the main source of data on orbitally-excited charmed baryons. Now BaBar and Belle are discovering new states, denoted by the outlined levels in Fig. 5. The Belle Collaboration observed an excited $\Sigma_c$ candidate decaying to $\Lambda_c^-\pi^+$, with mass about 510 MeV above $M(\Lambda_c)$ $^{40}$. The value of its $J^P$ shown in Fig. 5 is a guess, using the diquark ideas of $^{44}$. The highest $\Sigma_c$ levels were reported by Belle in Ref. $^{41}$. The highest $\Lambda_c$ is seen by BaBar in the decay mode $D^0 p$ $^{42}$.

In Fig. 5 the first excitations of the $\Lambda_c$ and $\Sigma_c$ are similar, scaling well from the first $\Lambda$ excitations $\Lambda(1405, 1/2^-)$ and $\Lambda(1520, 3/2^-)$. They have the same cost in $\Delta L$ (about 300 MeV), and their $L \cdot S$ splittings scale as $1/m_s$ or $1/m_c$. Higher $\Lambda_c$ states may correspond to excitation of a spin-zero $[ud]$ pair to $S = L = 1$, leading to many allowed $J^P$ values up to $5/2^-$. In $\Sigma_c$ the light-quark pair has $S = 1$; adding $L = 1$ allows $J^P \leq 5/2^-$. 
FIGURE 4. Lowest S-wave states with a single charmed quark. Only the $\Omega_c^*$ (dashed line denotes predicted mass) has not yet been reported.

FIGURE 5. Singly-charmed baryons and some of their orbital excitations.

States with higher $L$ may be narrower as a result of increased barrier factors affecting their decays, but genuine spin-parity analyses would be very valuable.
FIGURE 6. Charmed-strange mesons with $L = 0$ (negative-parity) and $L = 1$ (positive-parity). Here $j^P$ denotes the total light-quark spin + orbital angular momentum and the parity $P$.

Lowest charmed-strange $0^+, 1^+$ states

In the past couple of years the lowest $J^P = 0^+$ and $1^+ c\bar{s}$ states turned out to have masses well below most expectations. If they had been as heavy as the already-seen $c\bar{s}$ states with $L = 1$, the $D_{s1}(2536) [J^P = 1^+]$ and $D_{s2}(2573) [J^P = 2^+]$, they would have been able to decay to $D\bar{K}$ (the $0^+$ state) and $D^*\bar{K}$ (the $1^+$ state). Instead several groups [43] observed a narrow $D_{s}(2317) \equiv D_{s0}^*$ decaying to $\pi^0 D_s$ and a narrow $D_{s}(2460) \equiv D_{s1}^*$ decaying to $\pi^0 D_{s}^*$, as illustrated in Fig. 6. Their low masses allow the isospin-violating and electromagnetic decays of $D_{s0}^*$ and $D_{s1}^*$ to be observable. The decays $D_{s}(2460) \to D_s \gamma$ and $D_s(2460) \to D_s \pi^+ \pi^-$ also have been seen [37, 44], and the absolute branching ratios $\mathcal{B}(D_{s1}^* \to \pi^0 D_{s}^*) = (0.56 \pm 0.13 \pm 0.09)\%$, $\mathcal{B}(D_{s1}^* \to \gamma D_{s}) = (0.16 \pm 0.04 \pm 0.03)\%$, $\mathcal{B}(D_{s1}^* \to \pi^+ \pi^- D_{s}^*) = (0.04 \pm 0.01)\%$ measured.

The selection rules in decays of these states show their $J^P$ values are consistent with $0^+$ and $1^+$. Low masses are predicted [45] if these states are viewed as parity-doublets...
of the $D_s(0^-)$ and $D_s^*(1^-)$ $c\bar{s}$ ground states in the framework of chiral symmetry. The splitting from the ground states is 350 MeV in each case. Alternatively, one can view these particles as bound states of $D^{(*)}K$, perhaps bound by the transitions $(c\bar{q})(q\bar{s}) \leftrightarrow (c\bar{s})$ (the binding energy in each case would be 41 MeV), or as $c\bar{s}$ states with masses lowered by coupling to $D^{(*)}K$ channels [46, 47, 48].

**D$^+$ and $D_s$ decay constants**

CLEO has reported the first significant measurement of the $D^+$ decay constant: $f_{D^+} = (222.6\pm 16.7^{+2.8}_{-3.4})$ MeV [49]. This is consistent with lattice predictions, including one [50] of $(201\pm 3\pm 17)$ MeV. The accuracy of the previous world average [5] $f_{D^+} = (267\pm 33)$ MeV has been improved by a BaBar value $f_{D^+} = 283\pm 17\pm 7\pm 14$ MeV [51] and a new CLEO value $f_{D_s} = 280.1\pm 11.6\pm 6.0$ MeV [52]. The latter, when combined with CLEO’s $f_D$, leads to $f_{D^+}/f_D = 1.26\pm 0.11\pm 0.03$. A lattice prediction for $f_{D_s}$ [50] is $f_{D_s} = 249\pm 3\pm 16$ MeV, leading to $f_{D^+}/f_D = 1.24\pm 0.01\pm 0.07$. One expects $f_{B_s}/f_B \simeq f_{D^+}/f_D$ so better measurements of $f_{D_s}$ and $f_D$ by CLEO will help validate lattice calculations and provide input for interpreting $B_s$ mixing. A desirable error on $f_{B_s}/f_B \simeq f_{D^+}/f_D$ is $\leq 5\%$ for useful determination of CKM element ratio $|V_{td}/V_{ts}|$, needing errors $\leq 10$ MeV on $f_{D_s}$ and $f_D$. The ratio $|V_{td}/V_{ts}| = 0.208^{+0.008}_{-0.006}$ is implied by a recent CDF result on $B_s-\bar{B}_s$ mixing [53] combined with $B-\bar{B}$ mixing and $\xi \equiv (f_{B_s}\sqrt{V_{td}}/f_B\sqrt{V_{ts}}) = 1.21^{+0.047}_{-0.035}$ from the lattice [54]. A simple quark model scaling argument anticipated $f_{D_s}/f_D \simeq f_{B_s}/f_B \simeq \sqrt{|m_t/m_d|} \simeq 1.25$, where $m_s \simeq 485$ MeV and $m_d \simeq 310$ MeV are constituent quark masses [55].

**BEAUTY HADRONS**

The spectrum of ground-state hadrons containing a single $b$ quark is shown in Fig. 7. The following are a few recent high points of beauty hadron spectroscopy.

The CDF Collaboration has identified events of the form $B_s \rightarrow J/\psi \pi^\pm$, allowing for the first time a precise determination of the mass: $M = (6276.5\pm 4.0\pm 2.7)$ MeV/c$^2$ [56]. This is in reasonable accord with the latest lattice prediction of $6304\pm 12\pm 18$ MeV [57].

The long-awaited $B_s-\bar{B}_s$ mixing has finally been observed [52, 58]. The CDF value, $\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07$ ps$^{-1}$, constrains $f_{B_s}$ and $|V_{td}/V_{ts}|$, as mentioned earlier.

The Belle Collaboration has observed the decay $B \rightarrow \tau\nu\tau$ [59], leading to $f_B|V_{ub}| = (7.73^{+1.24+0.66}_{-1.02-0.58}) \times 10^{-4}$ GeV. When combined with an estimate [60] $f_{B_d} = (191\pm 27)$ MeV, this leads to $|V_{ub}| = (4.05\pm 0.89) \times 10^{-3}$, which is squarely in the range of recent averages [61].

A new CDF value for the $\Lambda_b$ lifetime, $\tau(\Lambda_b) = (1.59\pm 0.08\pm 0.03)$ ps, was reported at this Conference [62]. Whereas the previous world average of $\tau(\Lambda_b)$ was about 0.8 that of $B^0$, below theoretical predictions, the new CDF value substantially increases the world average to a value $\tau(\Lambda_b) = (1.410\pm 0.054)$ ps which is $0.923 \pm 0.036$ that of $B^0$ and quite comfortable with theory.
FIGURE 7. S-wave hadrons containing a single beauty quark. Dashed lines denote predicted levels not yet observed.

CHARMONIUM

Observation of the $h_c$

The $h_c(1^1P_1)$ state of charmonium has been observed by CLEO [63, 64] via $\psi(2S) \rightarrow \pi^0 h_c$ with $h_c \rightarrow \gamma \eta_c$ (transitions denoted by red (dark) arrows in Fig. 8 [65]).

Hyperfine splittings test the spin-dependence and spatial behavior of the $Q\bar{Q}$ force. Whereas these splittings are $M(J/\psi) - M(\eta_c) \simeq 115$ MeV for 1S and $M(\psi') - M(\eta'_c) \simeq 49$ MeV for 2S levels, P-wave splittings should be less than a few MeV since the potential is proportional to $\delta^3(\vec{r})$ for a Coulomb-like $c\bar{c}$ interaction. Lattice QCD [66] and relativistic potential [67] calculations confirm this expectation. One expects $M(h_c) \equiv M(1^1P_1) \simeq \langle M(3P_J) \rangle = 3525.36 \pm 0.06$ MeV.

Earlier $h_c$ sightings [63, 64] based on $\bar{p}p$ production in the direct channel, include a few events at $3525.4 \pm 0.8$ MeV seen in CERN ISR Experiment R704; a state at $3526.2 \pm 0.15 \pm 0.2$ MeV, decaying to $\pi^0 J/\psi$, reported by Fermilab E760 but not confirmed by Fermilab E835; and a state at $3525.8 \pm 0.2 \pm 0.2$ MeV, decaying to $\gamma \eta_c$ with $\eta_c \rightarrow \gamma \gamma$, reported by E835 with about a dozen candidate events [68].
In the CLEO data, both inclusive and exclusive analyses see a signal near $\langle M(3P_J) \rangle$. The exclusive analysis reconstructs $\eta_c$ in 7 decay modes, while no $\eta_c$ reconstruction is performed in the inclusive analysis. The exclusive signal is shown on the left in Fig. 9. A total of 19 candidates were identified, with a signal of $17.5 \pm 4.5$ events above background. The mass and product branching ratio for the two transitions are $M(h_c) = (3523.6 \pm 0.9 \pm 0.5)$ MeV; $\mathcal{B}_1(\psi' \to \pi^0 h_c)\mathcal{B}_2(h_c \to \gamma \eta_c) = (5.3 \pm 1.5 \pm 1.0) \times 10^{-4}$. The result of one of two inclusive analyses is shown on the right in Fig. 9. These yield $M(h_c) = (3524.9 \pm 0.7 \pm 0.4)$ MeV, $\mathcal{B}_1\mathcal{B}_2 = (3.5 \pm 1.0 \pm 0.7) \times 10^{-4}$. Combining exclusive and inclusive results yields $M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV, $\mathcal{B}_1\mathcal{B}_2 = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$. The $h_c$ mass is $(1.0 \pm 0.6 \pm 0.4)$ MeV below $\langle M(3P_J) \rangle$, barely consistent with the (nonrelativistic) bound $M(h_c) \geq \langle M(3P_J) \rangle$ and indicating little P-wave hyperfine splitting in charmonium. The value of $\mathcal{B}_1\mathcal{B}_2$ agrees with theoretical estimates of $(10^{-3} \cdot 0.4)$.

**FIGURE 8.** Transitions among low-lying charmonium states. From Ref. [65].
Decays of the $\psi'' \equiv \psi(3770)$

The $\psi''(3770)$ is a potential “charm factory” for present and future $e^+e^-$ experiments. At one time $\sigma(e^+e^- \rightarrow \psi'')$ seemed larger than $\sigma(e^+e^- \rightarrow \psi'' \rightarrow D\bar{D})$, raising the question of whether there were significant non-$D\bar{D}$ decays of the $\psi''$ \[70\]. A new CLEO measurement \[71\], $\sigma(\psi'') = (6.38 \pm 0.08^{+0.41}_{-0.30})$ nb, appears very close to the CLEO value $\sigma(D\bar{D}) = 6.39 \pm 0.10^{+0.17}_{-0.08}$ nb \[39\], leaving little room for non-$D\bar{D}$ decays. Some question has nonetheless been raised by two very new BES analyses \[72\] in which a significant non-$D\bar{D}$ component could still be present.

One finds that $\mathcal{B}(\psi'' \rightarrow \pi\pi J/\psi, \gamma\chi_{cJ}, \ldots)$ sum to at most 1–2%. Moreover, both CLEO and BES \[73\], in searching for enhanced light-hadron modes, find only that the $\rho\pi$ mode, suppressed in $\psi(2S)$ decays, also is suppressed in $\psi''$ decays.

Some branching ratios for $\psi'' \rightarrow XJ/\psi$ \[74\] are $\mathcal{B}(\psi'' \rightarrow \pi^+\pi^- J/\psi) = (0.189 \pm 0.020 \pm 0.020)\%$, $\mathcal{B}(\psi'' \rightarrow \pi^0\pi^0 J/\psi) = (0.080 \pm 0.025 \pm 0.016)\%$, $\mathcal{B}(\psi'' \rightarrow \eta J/\psi) = (0.087 \pm 0.033 \pm 0.022)\%$, and $\mathcal{B}(\psi'' \rightarrow \pi^0 J/\psi) < 0.028\%$. The value of $\mathcal{B}[\psi''(3770) \rightarrow \pi^+\pi^- J/\psi]$ found by CLEO is a bit above 1/2 that reported by BES \[75\]. These account for less than 1/2% of the total $\psi''$ decays.

CLEO has recently reported results on $\psi'' \rightarrow \gamma\chi_{cJ}$ partial widths, based on the exclusive process $\psi'' \rightarrow \gamma\chi_{cJ,1,2} \rightarrow \gamma\gamma J/\psi \rightarrow \gamma\ell^+\ell^-\bar{\ell}\bar{\ell}$ \[76\] and reconstruction of exclusive $\chi_{cJ}$ decays \[77\]. The results are shown in Table 1 implying $\sum_j \mathcal{B}(\psi'' \rightarrow \gamma\chi_{cJ}) = 6(1\%)$.

Several searches for $\psi''(3770) \rightarrow (\text{light hadrons})$, including $\text{VP, } K_sK_S$, and multi-body final states have been performed. Two CLEO analyses \[78,79\] find no evidence for any light-hadron $\psi''$ mode above expectations from continuum production except $\phi\eta$, indicating no obvious signature of non-$D\bar{D}$ $\psi''$ decays.
TABLE 1. CLEO results on radiative decays $\psi'' \to \gamma \chi_{cJ}$. Theoretical predictions of [80] are (a) without and (b) with coupled-channel effects; (c) shows predictions of [70].

| Mode   | Predicted (keV) | CLEO          |
|--------|-----------------|---------------|
|        | (a)  | (b)  | (c)  |                  |
| $\gamma \chi_{c2}$ | 3.2  | 3.9  | 24±4 | $< 21$          |
| $\gamma \chi_{c1}$ | 183  | 59   | 73±9 | 75±18          |
| $\gamma \chi_{c0}$ | 254  | 225  | 523±12 | 172±30         |

FIGURE 10. Belle distribution in $M(\pi^+ \pi^- J/\psi)$ for the $X(3872)$ region [86].

**X(3872): A 1++ molecule**

Many charmonium states above $D\bar{D}$ threshold have been seen recently. Reviews may be found in Refs. [81, 82]. The $X(3872)$, discovered by Belle in $B$ decays [83] and confirmed by BaBar [84] and in hadronic production [85], decays predominantly into $J/\psi \pi^+ \pi^-$. Evidence for it is shown in Fig. [10] [86]. Since it lies well above $D\bar{D}$ threshold but is narrower than experimental resolution (a few MeV), unnatural $J^P = 0^-, 1^+, 2^-$ is favored. It has many features in common with an S-wave bound state of $(D^0\bar{D}^{*0} + \bar{D}^0D^{*0})/\sqrt{2} \sim c\bar{c}u\bar{u}$ with $J^{PC} = 1^{++}$ [87]. The simultaneous decay of $X(3872)$ to $\rho J/\psi$ and $\omega J/\psi$ with roughly equal branching ratios is a consequence of this “molecular” assignment.

Analysis of angular distributions [88] in $X \to \rho J/\psi, \omega J/\psi$ favors the $1^{++}$ assignment [86]. (See also [44, 82].) The detection of the $\gamma J/\psi$ mode ($\sim 14\%$ of $J/\psi \pi^+ \pi^-$) [89] confirms the assignment of positive $C$ and suggests a $c\bar{c}$ admixture in the wave function. BaBar [90] finds $\mathcal{B}[X(3872) \to \pi^+ \pi^- J/\psi] > 0.042$ at 90% c.l.
glueball or 3.3σ fluctuation
unresolved puzzle of J/ψ X

**FIGURE 11.** Left: evidence for an excited $2^3P_2(\chi'_{c2})$ state (combined $D^0\bar{D}^0$ and $D^+D^-$ spectrum) [91]. Right: Spectrum of masses recoiling against $J/\psi$ in $e^+e^- \rightarrow J/\psi + X$ [92].

### Additional states around 3940 MeV

Belle has reported a candidate for a $2^3P_2(\chi'_{c2})$ state in $\gamma\gamma$ collisions [91], decaying to $DD$ (left panel of Fig. 11). The angular distribution of $DD$ pairs is consistent with $\sin^4 \theta^*$ as expected for a state with $J = 2, \lambda = \pm 2$. It has $M = 3929 \pm 5 \pm 2$ MeV, $\Gamma = 29 \pm 10 \pm 3$ MeV, and $\Gamma_{eeB}(DD) = 0.18 \pm 0.06 \pm 0.03$ eV, all reasonable for a $\chi'_{c2}$ state.

A charmonium state $X(3938)$ (the right-most peak in the right panel of Fig. 11) is produced recoiling against $J/\psi$ in $e^+e^- \rightarrow J/\psi + X$ [92] and is seen decaying to $D\bar{D}^* + c.c.$ Since all lower-mass states observed in this recoil process have $J = 0$ (these are the $\eta_c(1S), \chi_{c0}$ and $\eta'(2S)$; see the Figure), it is tempting to identify this state with $\eta_c(3S)$ (not $\chi'_{c0}$, which would decay to $DD$).

The $\omega J/\psi$ final state in $B \rightarrow K\omega J/\psi$ shows a peak above threshold at $M(\omega J/\psi) \simeq 3940$ MeV [93]. This could be a candidate for one or more excited P-wave charmonium states, likely the $\chi'_{c1,2}(2^3P_{1,2})$. The corresponding $b\bar{b}$ states $\chi'_{b1,2}$ have been seen to decay to $\omega \Upsilon(1S)$ [94].

### The $Y(4260)$

Last year BaBar reported a state $Y(4260)$ produced in the radiative return reaction $e^+e^- \rightarrow \gamma\pi^+\pi^- J/\psi$ and seen in the $\pi^+\pi^- J/\psi$ spectrum [95] (see Fig. 12). Its mass is consistent with being a $4S$ level [96] since it lies about 230 MeV above the $3S$ candidate (to be compared with a similar 4S-3S spacing in the $\Upsilon$ system). Indeed, a $4S$ charmonium level at 4260 MeV/$c^2$ was anticipated on exactly this basis [97]. With this assignment, the $nS$ levels of charmonium and bottomonium are remarkably congruent to one another, as shown in Fig. 13. Their spacings would be identical if the interquark potential were $V(r) \sim \log(r)$, which may be viewed as an interpolation between the short-distance $\sim -1/r$ and long-distance $\sim r$ behavior expected in QCD. Other interpretations of $Y(4260)$ include a $cs\bar{c}\bar{s}$ state [98] and a hybrid $c\bar{c}g$ state [99], for which it lies in the expected mass range.
FIGURE 12. Evidence for the $Y(4260)$ [95].

FIGURE 13. Congruence of charmonium and bottomonium spectra if the $Y(4260)$ is a 4S level.
FIGURE 14. Evidence for $Y(4260)$ from a direct scan by CLEO [100].

The CLEO Collaboration has confirmed the $Y(4260)$, both in a direct scan [100] and in radiative return [101]. Results from the scan are shown in Fig. 14, including signals for $Y(4260) \rightarrow \pi^+\pi^-J/\psi$ (11σ), $\pi^0\pi^0J/\psi$ (5.1σ), and $K^+K^-J/\psi$ (3.7σ). There are also weak signals for $\psi(4160) \rightarrow \pi^+\pi^-J/\psi$ (3.6σ) and $\pi^0\pi^0J/\psi$ (2.6σ), consistent with the $Y(4260)$ tail, and for $\psi(4040) \rightarrow \pi^+\pi^-J/\psi$ (3.3σ).

The hybrid interpretation of $Y(4260)$ deserves further attention. One consequence is a predicted decay to $D\bar{D}_1 + c.c.$, where $D_1$ is a P-wave $c\bar{q}$ pair. Now, $D\bar{D}_1$ threshold is 4287 MeV/$c^2$ if we consider the lightest $D_1$ to be the state noted in Ref. [5] at 2422 MeV/$c^2$. In this case the $Y(4260)$ would be a $D\bar{D}_1 + c.c.\ bound\ state$. It would decay to $D\pi\bar{D}^*$, where the $D$ and $\pi$ are not in a $D^*$. The dip in $R_{e^+e^-}$ lies just below $D\pi\bar{D}^*$ threshold, which may be the first S-wave meson pair accessible in $c\bar{c}$ fragmentation [102].

**Charmonium: updated**

Remarkable progress has been made in the spectroscopy of charmonium states above charm threshold in the past few years. Fig. 15 summarizes the levels (some of whose assignments are tentative). Even though such states can decay to charmed pairs (with the possible exception of $X(3872)$, which may be just below $D\bar{D}^*$ threshold), other decay modes are being seen. I have not had time to discuss much other interesting work by BES and CLEO on exclusive decays of the $\chi_{cJ}$ and $\psi(2S)$ states, including studies of strong-electromagnetic interference in $\psi(2S)$ decays.

**THE $\Upsilon$ FAMILY (BOTTOMONIUM)**

Some properties and decays of the $\Upsilon (b\bar{b})$ levels are summarized in Fig. 16. Masses are in agreement with unquenched lattice QCD calculations, a triumph of theory [103]. Direct
**FIGURE 15.** Charmonium states including levels above charm threshold.

**FIGURE 16.** $b\bar{b}$ levels and some decays. Electric dipole (E1) transitions $S \leftrightarrow P \leftrightarrow D$ are not shown.
photons have been observed in 1S, 2S, and 3S decays, implying estimates of the strong fine-structure constant consistent with others [104]. The transitions $\chi_b(2P) \rightarrow \pi \pi \chi_b(1P)$ have been seen [105, 106]. In addition to the $\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)$ transitions noted in Fig. [107], Belle has seen $\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, with a branching ratio $B = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$ [108].

### Remeasurement of $\Upsilon(nS)$ properties

New values of $B[\Upsilon(1S, 2S, 3S) \rightarrow \mu^+ \mu^-] = (2.39 \pm 0.02 \pm 0.07, 2.03 \pm 0.03 \pm 0.08, 2.39 \pm 0.07 \pm 0.10\%$ [109], when combined with new measurements $\Gamma_{ee}(1S, 2S, 3S) = (1.354 \pm 0.004 \pm 0.020, 0.619 \pm 0.004, \pm 0.010, 0.446 \pm 0.004 \pm 0.007) \text{ keV}$ imply total widths $\Gamma_{tot}(1S, 2S, 3S) = (54.4 \pm 0.2 \pm 0.8 \pm 1.6, 30.5 \pm 0.2 \pm 0.5 \pm 1.3, 18.6 \pm 0.2 \pm 0.3 \pm 0.9) \text{ keV}$. The values of $\Gamma_{tot}(2S, 3S)$ are significantly below world averages [5], which will lead to changes in comparisons of predicted and observed transition rates. As one example, the study of $\Upsilon(2S, 3S) \rightarrow \gamma X$ decays [110] has provided new branching ratios for E1 transitions to $\chi_{bJ}(1P)$, $\chi_{bJ}^\prime(2P)$ states. These may be combined with the new total widths to obtain updated partial decay widths [line (a) in Table 2], which may be compared with one set of non-relativistic predictions [111] [line (b)]. The suppression of transitions to $J = 0$ states by 10–20% with respect to non-relativistic expectations agrees with relativistic predictions [112]. The partial width for $\Upsilon(3S) \rightarrow \gamma 1^3P_0$ is found to be $56 \pm 20 \text{ eV}$, about eight times the highly-suppressed value predicted in Ref. [111]. That prediction is very sensitive to details of wave functions; the discrepancy indicates the importance of relativistic distortions.

### $b\bar{b}$ spin singlets

Decays of the $\Upsilon(1S, 2S, 3S)$ states are potential sources of information on $b\bar{b}$ spin-singlets, but none has been seen yet. One expects 1S, 2S, and 3S hyperfine splittings to be approximately 60, 30, 20 MeV/c², respectively [113]. The lowest P-wave singlet state (“$h_b$”) is expected to be near $M(1^3P_2) \approx 9900 \text{ MeV/c}^2$ [116].

Several searches have been performed or are under way in 1S, 2S, and 3S CLEO data. One can search for the allowed M1 transition in $\Upsilon(1S) \rightarrow \gamma \eta_b(1S)$ by reconstructing exclusive final states in $\eta_b(1S)$ decays and dispensing with the soft photon, which is likely to be swallowed up in background. Final states are likely to be of high multiplicity.

One can search for higher-energy but suppressed M1 photons in $\Upsilon(nS) \rightarrow \gamma \eta_b(nS) (n \neq n')$ decays. These searches already exclude many models. The strongest

| $\Gamma$ (keV) | $2S \rightarrow 1P_J$ transitions | $3S \rightarrow 2P_J$ transitions |
|---------------|----------------------------------|----------------------------------|
| $J = 0$       | $J = 1$                          | $J = 2$                          |
| 1.14±0.16     | 2.11±0.16                        | 2.21±0.16                        |
| 1.39          | 2.18                             | 2.14                             |
| 1.26±0.14     | 2.71±0.20                        | 2.95±0.21                        |
| 1.65          | 2.52                             | 2.78                             |
upper limit obtained is for \( n' = 3, n = 1 \): \( \mathcal{B} \leq 4.3 \times 10^{-4} \) (90% c.l.). \( \eta_b \) searches using sequential processes \( \Upsilon(3S) \to \pi^0 \eta_b (1 ^1P_1) \to \pi^0 \eta \eta_b (1S) \) and \( \Upsilon(3S) \to \gamma \eta' b_0 \to \gamma \eta \eta_b (1S) \) (the latter suggested in Ref. \cite{114}) are being conducted but there are no results yet. Additional searches for \( h_b \) involve the transition \( \Upsilon(3S) \to \pi^+ \pi^- h_b \) [for which a typical experimental upper bound based on earlier CLEO data \cite{115}] is \( \mathcal{O}(10^{-3}) \), with a possible \( h_b \to \gamma \eta \eta \) transition expected to have a 40% branching ratio \cite{116}.

**FUTURE PROSPECTS**

Two main sources of information on hadron spectroscopy in the past few years have been BES-II and CLEO. BES-II has ceased operation to make way for BES-III. CLEO’s original goals of 3 fb\(^{-1}\) at \( \psi(3770) \), 3 fb\(^{-1}\) above \( D_s \) pair threshold, and \( 10^9 \) \( J/\psi \) now appear unrealistic in light of attainable CESR luminosity. Consequently, it was agreed to focus CLEO on 3770 and 4170 MeV, split roughly equally, yielding about 750 pb\(^{-1}\) at each energy if current luminosity projections hold. The determination of \( f_{D}, f_{D_s} \), and form factors for semileptonic \( D \) and \( D_s \) decays will provide incisive tests for lattice gauge theories and measure CKM factors \( V_{cd} \) and \( V_{cs} \) with unprecedented precision. A sample of 30 million \( \psi(2S) \) (about 10 times the current number) is planned to be taken, with at least 10 million this summer. Some flexibility to explore new phenomena will be maintained. CLEO-c running will end at the end of March 2008; BES-III and and PANDA will carry the torch thereafter.

Belle has taken 3 fb\(^{-1}\) of data at \( \Upsilon(3S) \); it is anyone’s guess what they will find with such a fine sample. For comparison, CLEO has (1.1,1.2,1.2) fb\(^{-1}\) at (1S,2S,3S). Both BaBar and Belle have shown interest in hadron spectroscopy and are well-positioned to study it. There have been significant contributions from CDF and D0 as well, and we look forward to more.

**SUMMARY**

Hadron spectroscopy is providing both long-awaited states like \( h_c \) (whose mass and production rate confirm theories of quark confinement and isospin-violating \( \pi^0 \)-emission transitions) and surprises like low-lying P-wave \( D_s \) mesons, X(3872), X(3940), Y(3940), Z(3940) and Y(4260). Decays of \( \psi''(3770) \) shed light on its nature as a \( 1^3D_1 \) \( c\bar{c} \) state with a small S-wave admixture.

Upon reflection, some properties of the new hadron states may be less surprising but we are continuing to learn about properties of QCD in the strong-coupling regime. There is evidence for molecules, 3S, 2P, 4S or hybrid charmonium, and interesting decays of states above flavor threshold.

QCD may not be the last strongly coupled theory with which we have to deal. The mystery of electroweak symmetry breaking or the very structure of quarks and leptons may require related techniques. It is important to realize that insights on hadron spectra are coming to us in general from experiments at the frontier of intensity and detector capabilities rather than energy, and illustrate the importance of a diverse approach to the fundamental structure of matter.
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REFERENCES

1. R. L. Jaffe, this Conference
2. M. Karliner and H. J. Lipkin, Phys. Lett. B 638, 221 (2006).
3. R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. 91, 232003 (2003).
4. F. Wilczek, hep-ph/0409168 in From fields to strings: Circumnavigating theoretical physics: Ian Kogan memorial collection, edited by M. Shifman et al., vol. 1 (World Scientific, Singapore, 2005), p. 77; A. Selem, Senior Thesis, M.I.T., 2005 (unpublished); A. Selem and F. Wilczek, hep-ph/0602128 in Proc. Ringberg Workshop On New Trends In HERA Physics 2005, 2–7 October 2005, Tegernsee, Germany, edited by G. Grindhammer et al. (World Scientific, Hackensack, NJ, 2006), p. 337.
5. W.-M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006).
6. L. S. Brown and R. L. Goble, Phys. Rev. D 4, 723 (1971).
7. E. van Beveren, et al., Z. Phys. C 30, 615 (1986).
8. A. Dobado and J. R. Peláez, Phys. Rev. D 47, 4883 (1993); ibid. 56, 3057 (1997).
9. R. L. Goble and J. L. Rosner, Phys. Rev. D 5, 2345 (1972); R. L. Goble, R. Rosenfeld and J. L. Rosner, Phys. Rev. D 39, 3264 (1989).
10. S. M. Roy, Phys. Lett. 36B, 353 (1971).
11. I. Caprini, G. Colangelo, and H. Leutwyler, Phys. Rev. Lett. 96, 132001 (2006).
12. E. van Beveren, D. V. Bugg, F. Kleefeld and G. Rupp, arXiv:hep-ph/0606022.
13. M. Pennington, hep-ph/0604212.
14. E. M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 86, 770 (2001); I. Bediaga, Braz. J. Phys. 34, 1398 (2004).
15. M. Ablikim et al. [BES Collaboration], Phys. Lett. B 598, 149 (2004).
16. D. V. Bugg, arXiv:hep-ph/0608081.
17. D. V. Bugg, arXiv:hep-ex/0510014.
18. J. Oller, Phys. Rev. D 71, 054030 (2005) and references therein; S. Descotes-Genon and B. Mousallam, arXiv:hep-ph/0607133.
19. E. M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 89, 121801 (2002); hep-ex/0507099 Phys. Rev. D 73, 032004 (2006).
20. M. Ablikim et al. [BES Collaboration], Phys. Lett. B 633, 681 (2006).
21. D. V. Bugg, Phys. Lett. B 632, 471 (2006), and references therein.
22. C. Cawlfield et al. [CLEO Collaboration], hep-ex/0606045, submitted to Phys. Rev. D.
23. J. L. Rosner, Enrico Fermi Institute report EFI 06-14, hep-ph/0608102, August 2006.
24. B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 95, 121802 (2005).
25. K. Abe et al. [Belle Collaboration], Moriond 2006.
26. D. M. Asner et al. [CLEO Collaboration], Phys. Rev. D 70, 091101(R) (2004).
27. B. Aubert et al. [BaBar Collaboration], hep-ex/0605003.
28. M. Chanowitz, Phys. Rev. Lett. 95, 172001 (2005).
29. M. Campbell, M. S. Thesis, Univ. of Glasgow, 1997, as quoted in R. A. Briere et al., CLNS-01-1742.
30. S. Giovanella, this Conference. The method used to extract the gluon content of $\eta'$ was suggested by J. Rosner, Phys. Rev. D 27, 1101 (1983).
31. F. E. Close and Q. Zhao, Phys. Rev. D 71, 094022 (2005).
32. D. Besson et al. [CLEO Collaboration], hep-ex/0512003, submitted to Phys. Rev. D.
33. C. McNeile, C. Michael and P. Pennanen [UKQCD Collaboration], Phys. Rev. D 65, 094505 (2002); C. Michael, hep-ph/0308293; C. McNeile and C. Michael [UKQCD Collaboration], Phys. Rev. D 73, 074506 (2006); T. Burns and F. E. Close, hep-ph/0604161.
34. G. S. Adams et al. [E852 Collaboration], Phys. Rev. Lett. 81, 5760 (1998).
35. A. R. Dzierba et al., Phys. Rev. D 73, 072001 (2006).
36. C. McNeile, C. Michael and P. Pennanen [UKQCD Collaboration], Phys. Rev. D 65, 094505 (2002); C. Michael, hep-ph/0308293; C. McNeile and C. Michael [UKQCD Collaboration], Phys. Rev. D 73, 074506 (2006); T. Burns and F. E. Close, hep-ph/0604161.
37. U. Mallik, this Conference.
38. T. Tsuboyama, this Conference.
39. R. Briere, this Conference.
40. R. Mizuk et al. [Belle Collaboration], hep-ex/0512003, submitted to Phys. Rev. D.
41. T. Lesiak [for the Belle Collaboration], hep-ex/0605003, submitted to Phys. Rev. D.
42. B. Aubert et al. [BaBar Collaboration], hep-ex/0603052, submitted to Phys. Rev. Letters.
43. B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 90, 242001 (2003); D. Besson et al. [CLEO Collaboration], Phys. Rev. D 68, 032002 (2003); K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 92, 012002 (2004).
44. H. Marsiske, at Flavor Physics and CP Violation Conference, Vancouver, BC, April, 2006; B. Aubert et al. [BaBar Collaboration], hep-ex/0605036, submitted to Phys. Rev. D; S. J. Gowdy [for the BaBar Collaboration], at Moriond 2006 (QCD and Hadronic Interactions at High Energy), hep-ex/0605047.
45. W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003), and refs. therein.
46. E. van Beveren and G. Rupp, Phys. Rev. Lett. 91, 012003 (2003); Eur. Phys. J. C 32, 493 (2004).
47. F. E. Close, Int. J. Mod. Phys. A 20, 5156 (2005) [arXiv:hep-ph/0411396].
48. Very recently a $D_s$ state has been observed at 2.86 GeV/c$^2$ decaying to $DK$. See B. Aubert et al. [BaBar Collaboration], hep-ex/0607082.
49. M. Artuso et al. [CLEO Collaboration], Phys. Rev. Lett. 95, 251801 (2005).
50. C. Aubin et al., Phys. Rev. Lett. 95, 122002 (2005).
51. B. Aubert et al. [BABAR Collaboration], hep-ex/0607094.
52. S. Stone [CLEO Collaboration], presented at ICHEP 06, Moscow, Russia, 26 July – 2 August 2006, http://ichep06.jinr.ru/reports/179_10s2_18p05_Stone.pdf.
53. A. Abulencia et al. [CDF Collaboration], hep-ex/0606027.
54. M. Okamoto, PoS LAT2005, 013 (2006), hep-lat/0510113.
55. J. L. Rosner, Phys. Rev. D 44, 3732 (1990).
56. M. Aoki [for the CDF Collaboration], presented to Quarkonium Working Group, Brookhaven Natl. Lab., June 27–30, 2006, updating W. Wester, Nucl. Phys. B Proc. Suppl. 156, 240 (2006); D. Acosta et al., Phys. Rev. Lett. 96, 082002 (2006).
57. I. F. Allison, C. T. H. Davies, A. Gray, A. S. Kronfeld, P. B. Mackenzie and J. N. Simone [HPQCD Collaboration], Phys. Rev. Lett. 94, 172001 (2005).
58. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 97, 021802 (2006).
59. K. Ikado et al. [Belle Collaboration], hep-ex/0604018, submitted to Phys. Rev. Lett.; hep-ex/0605008, at 4th Flavor Physics and CP Violation Conference (FPCP 2006), Vancouver, BC.
60. A. Höcker and Z. Ligeti, hep-ph/0605217.
61. Periodic updates may be found at http://www.slac.stanford.edu/xorg/hfag/.
62. A. Kryemadhi, this Conference.
63. J. L. Rosner et al. [CLEO Collaboration], Phys. Rev. Lett. 95, 102003 (2005).
64. P. Rubin et al. [CLEO Collaboration], Phys. Rev. D 72, 092005 (2005).
65. D. Cassel and J. L. Rosner, CERN Courier 46 (5), June 2006, p. 33.
66. T. Manke et al. [CP-PACS Collaboration], Phys. Rev. D 62, 114508 (2000); M. Okamoto et al. [CP-PACS Collaboration], ibid. 65, 095408 (2002).
67. D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D 67, 014027 (2003); Mod. Phys. Lett. A 20, 1887 (2005).
68. M. Andreotti et al. [Fermilab E835 Collaboration], Phys. Rev. D 72, 032001 (2005).
69. J. Stubbe and A. Martin, Phys. Lett. B 271, 208 (1991).
