Heavy Quark Spectroscopy – Theory Overview

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Abstract. Some recent discoveries in the spectroscopy of hadrons containing heavy quarks, and some of their theoretical interpretations, are reviewed.

1. Introduction

The spectroscopy of states containing heavy quarks $Q$ has undergone a great renaissance in recent years, providing an exceptional window into tests of QCD. Quarkonium systems $QQ$ are amenable to perturbative descriptions of their decays. One can study $Qq$ and $Qqq$ hadrons ($q =$ light quark $u,d,s$) in which the heavy quarks play the role of “nuclei,” expanding observables in inverse powers of $m_Q$. Many heavy-quark hadrons have masses and couplings strongly affected by nearby thresholds, as has been known for many years in the physics of atoms and nuclei [1, 2, 3]. Hadron spectra often are crucial in separating electroweak physics from strong-interaction effects. More broadly, QCD may not be the only instance of important non-perturbative effects. Understanding how such effects are manifested in hadrons may help prepare us for surprises at the CERN Large Hadron Collider (LHC). Finally, at the quark and lepton level there exists an intricate level structure and a set of transitions calling for fundamental understanding; spectroscopic methods may help.

We begin this brief review by outlining some theoretical spectroscopic methods. We then discuss charmed and beauty hadrons, heavy quarkonium ($c\bar{c}$, $b\bar{b}$), and future prospects.

2. Theoretical methods

At large distances when the QCD coupling constant becomes too large to permit the use of perturbation theory, one can place quark and gluon degrees of freedom on a space-time lattice. An accurate description of the heavy quarkonium spectrum then can be obtained once one takes account of degrees of freedom associated with the pair production of light ($u,d,s$) quarks [4].

Perturbative QCD was applied to charmonium shortly after the discovery of asymptotic freedom [5]. It describes $c\bar{c}$ decays reasonably well and does better for $b\bar{b}$ decays, where relativistic corrections are smaller [6, 7].

At low energies neither lattice nor perturbative methods are appropriate for multiparticle systems. Older techniques of chiral dynamics, unitarity, and crossing symmetry provide valuable insights for describing dynamics of mesons up to the GeV scale and baryons somewhat higher.

Hadrons with one charmed or beauty quark can be regarded as “atoms” of QCD, with the light-quark and gluonic degrees of freedom playing the role of the electron(s) and the heavy quark playing the role of the nucleus. Properties of these systems tend to be very simple under the interchange $c \leftrightarrow b$, in the manner of isotope effects in nuclei. This heavy quark symmetry has led to a number of successful mass and coupling relations.

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For charmonium, and more quantitatively for bottomonium, states may be described as bound by a potential whose short-distance behavior is approximately Coulombic and whose long-distance behavior is linear to account for quark confinement. Such potential models, often supplemented by relativistic and/or coupled-channel corrections, provide approximate descriptions for masses, leptonic partial widths, and hyperfine and fine-structure splittings.

One can reproduce the spectrum of hadrons containing the $u$, $d$, and $s$ quarks with a model based on additive quark masses $m_i$ and hyperfine interactions proportional to $\langle \sigma_i \cdot \sigma_j / (m_i m_j) \rangle$. The masses of these “constituent” quarks are due in large part to their interaction with the surrounding gluon field. Correlations between quarks (“diquarks”) also may be important in such descriptions. Because of its increased coupling strength at long distances, QCD leads to the formation of condensates, including non-zero expectation values of color singlet quark-antiquark pairs and gluonic configurations such as instantons. A systematic attempt to cope with the effect of these condensates on hadron spectroscopy relies on QCD sum rules.

Various phenomenological methods exist for treating resonance decays. These mostly rely either on the notion that a single quark in a resonance undergoes a transition such as pion or photon emission, or the creation of a $q\bar{q}$ pair corresponding to the breaking of a flux tube connecting constituents of the resonance.

As this review emphasizes the variety of new experimental data on heavy-quark spectroscopy seeking theoretical explanation, it will concentrate on schemes such as lattice and perturbative QCD which have had the greatest predictive power. More extensive discussions and references for approaches mentioned above may be found in Refs. [10, 11]. Some details on experimental charm and charmonium results are given in the review of Ref. [12].

3. Charmed states

A summary of mesons and baryons containing one charmed quark in an S-wave is shown in Fig. 1(a). The most recent addition is the $\Omega_c^*$ [8], a $css$ candidate for the predicted $J = 3/2$ partner of the $\Omega^- = sss$. It lies $70.8 \pm 1.0 \pm 1.1$ MeV above the $\Omega_c$, in agreement with predictions [9].

### 3.1. Charmed baryons

Orbitally-excited charmed baryon levels are plotted along with those of the lowest $L = 0$ states in Fig. 1(b). The first excitations of the $\Lambda_c$ and $\Xi_c$ scale 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
Charmed-strange mesons with $L = 0$ (negative-parity), $L = 1$ (positive-parity), and candidate for state with $L = 2$ (positive parity). Here $j^P$ denotes the total light-quark spin + orbital angular momentum and the parity $P$.

$L \cdot S$ 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 $J^P \leq 5/2^-$. 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. Some recent results:

1. The $\Lambda_c(2880)$, first seen in the $\Lambda^+\pi^-\pi^+$ mode [13] and confirmed in the $D^0p$ mode by BaBar [14], has been shown to have likely $J^P = 5/2^+$ [15].

2. The highest $\Lambda_c$ was seen by BaBar in the decay mode $D^0p$ [14]. The Belle Collaboration has seen evidence for its decay to $\Sigma_c(2455)\pi$ [15].

3. An excited $\Sigma_c$ candidate has been seen decaying to $\Lambda_c\pi^+$, with mass about 510 MeV above $M(\Lambda_c)$ [16]. Its $J^P$ shown in Fig. 1(b) is a guess, using ideas of [17], and is consistent with the assignment proposed in [12] based on the prediction of [18].

4. The highest $\Xi_c$ levels were reported by the Belle Collaboration in Ref. [19], and confirmed by BaBar [20], both in the $\Lambda_c^+K^-\pi^+$ channel. Their masses suggest $L^P = 2^+$.  

3.2. Excited $D_{sJ}$ and $D$ states

Excited $D_{sJ}$ states are depicted in Fig. 2. The lowest $J^P = 0^+$ and $1^+$ $c\bar{s}$ states turned out much lighter than most expectations. If as heavy as the already-seen $c\bar{s}$ $L = 1$ states, $D_{s1}(2536)$ [$J^P = 1^+$] 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 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 $\pi^0 D_{s1}^*$ were seen \cite{21}. Their low masses allow isospin-violating and electromagnetic decays of $D_{s0}^*$ and $D_{s1}^*$ to be observable. The decays $D_s(2460) \rightarrow D_s\gamma$ and $D_s(2460) \rightarrow D_s\pi^+\pi^-$ also have been seen \cite{22}, and the absolute branching ratios $B(D_{s1}^* \rightarrow \pi^0 D_{s1}^*) = (0.56 \pm 0.13 \pm 0.09)\%$, $B(D_{s1}^* \rightarrow \gamma D_s) = (0.16 \pm 0.04 \pm 0.03)\%$, $B(D_{s1}^* \rightarrow \pi^+\pi^- D_{s1}^*) = (0.04 \pm 0.01)\%$ measured.

The selection rules in decays of these states show that their $J^P$ values are consistent with $0^+$ and $1^+$. Low masses are predicted \cite{23} if these states are viewed as chiral-symmetry parity-doublets of the $D_s(0^-)$ and $D_s^*(1^-) c\bar{s}$ ground states. The splitting from the ground states is 350 MeV in each case. Alternatively, one can view these particles as bound states of $D(s)^*(K)$ (the binding energy in each case would be 41 MeV), or as $c\bar{s}$ states with masses lowered by coupling to $D(s)^* K$ channels \cite{21, 23}. In either framework, light-quark degrees of freedom appear to be important in getting the $D_{s0}^*$ and $D_{s1}^*$ masses right.

A candidate for the first radial excitation of the $D_s^*(2112)$ has been seen by Belle in $B^+ \rightarrow D^0D^+K^+$ decays \cite{26} in the $M(D^0K^+)$ spectrum. Its mass and width are $(2715 \pm 11^{+14}_{-13})$ and $(115 \pm 20^{+36}_{-32})$ MeV/$c^2$. Its spin-parity is $J^P = 1^-$. It lies $(603^{+16}_{-18})$ MeV/$c^2$ above the ground state, in between the $2^3S_1\rightarrow 1^3S_1$ spacings of $(681 \pm 20)$ MeV/$c^2$ for $s\bar{s}$ and 589 MeV/$c^2$ for $c\bar{c}$ \cite{21}. This is as expected in a potential interpolating between $cc$ and $bb$ states \cite{28}, and as predicted in Ref. \cite{29}. (Ref. \cite{30} prefers to identify this state as the lowest $^3D_1 c\bar{s}$ level.)

A higher-lying $c\bar{s}$ state \cite{31} is seen by BaBar decaying to $D^0K^+ + D^+K_S$, so it must have natural spin-parity $0^+$, $1^-$, $2^+\ldots$. Its mass and width are $(2856.6 \pm 1.5 \pm 5.0)$ and $(48 \pm 7 \pm 10)$ MeV/$c^2$. It has been interpreted as a radial excitation of the $0^+$ state $D_{s0}(2317) \equiv D_{s}(2317)$ \cite{32, 33}, shown in Fig. \ref{fig:1} or a $^3(\bar{D}_2)$ state \cite{34}. The same experiment also sees a broad peak of marginal significance with $M = (2688 \pm 4 \pm 3)$ MeV/$c^2$, $\Gamma = (112 \pm 7 \pm 36)$ MeV/$c^2$.

In contrast to the lightest $0^+$, $1^+$ charmed-strange states, which are too light to decay to $DK$ or $D^* K$, the lightest $0^+$, $1^+$ charmed-nonstrange candidates appear to be heavy enough to decay to $D\pi$ or $D^*\pi$, and thus are expected to be broad. Heavy quark symmetry predicts the existence of a $0^+$, $1^+$ pair with light-quark total angular momentum and parity $j^P = 1/2^+$ decaying to $D\pi$ or $D^*\pi$, respectively, via a S-wave. A $1^+$, $2^+$ pair with $j^P = 3/2^+$, decaying primarily via a D-wave to $D^*\pi$ or both $D\pi$ and $D^*\pi$, respectively, is represented by states at $2422 \pm 1.3$ MeV/$c^2$ and 2461.1 \pm 1.6 MeV/$c^2$ \cite{21}. As for the $j^P = 1/2^+$ candidates, CLEO \cite{35} and Belle \cite{36} find a broad $1^+$ state in the range 2420–2460 MeV/$c^2$, while Belle and FOCUS \cite{36, 37, 38} find broad $0^+$ candidates near 2300 and 2400 MeV/$c^2$, respectively.

### 3.3. Charmed meson decay constants

CLEO’s value $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV \cite{39} is consistent with a lattice prediction \cite{10} of $(201 \pm 3 \pm 17)$ MeV. The accuracy of the previous world average \cite{21} for $f_{D_s} = (267 \pm 33)$ MeV has been improved by a BaBar value $f_{D_{s0}} = 283 \pm 17 \pm 7 \pm 14$ MeV \cite{41} and a new CLEO value $f_{D_{s1}} = 280.1 \pm 11.6 \pm 6$ MeV \cite{42}. The latter, when combined with CLEO’s $f_D$, leads to $f_{D_s}/f_D = 1.26 \pm 0.11 \pm 0.03$. A lattice prediction for $f_{D_s}$ \cite{10} is $f_{D_s} = 249 \pm 3 \pm 16$ MeV, leading to $f_{D_s}/f_D = 1.24 \pm 0.01 \pm 0.07$. One expects $f_{B_s}/f_B \approx f_{D_s}/f_D$ so better measurements of $f_{D_s}$ and $f_B$ by CLEO will help validate lattice calculations and provide input for interpreting $B_s$ mixing. A desirable error on $f_{B_s}/f_B \approx f_{D_s}/f_D$ 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 $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007$ (exp) $^{+0.0081}_{-0.0080}$ (theor) is implied by a recent CDF result on $B_s \rightarrow \bar{B}_s$ mixing \cite{43} combined with $B^-\bar{B}$ mixing and $\xi \equiv (f_{B_s}/\sqrt{B_{D_s}}) / (f_B/\sqrt{B_B}) = 1.21^{+0.037}_{-0.035}$ from the lattice \cite{44}. A simple quark model scaling argument anticipated $f_{D_s}/f_D \approx f_{B_s}/f_B \approx \sqrt{m_s/m_d} \approx 1.25$ \cite{45}.
4. Beauty hadrons

The spectrum of ground-state hadrons containing a single $b$ quark is shown in Fig. 3. The CDF Collaboration has published measurements of the $B_s$ and $\Lambda_b$ masses and the $B_s$–$B^0$ and $\Lambda_b$–$B^0$ mass differences which are of better precision than the current world averages [46]. With 1 fb$^{-1}$ CDF now has evidence for the long-sought $\Sigma_b^*$ and $\Sigma_b^{(*)*}$ states very near the masses predicted from the corresponding charmed baryons using heavy quark symmetry. (See [47] for some references.) The analysis of Ref. [48] studies the spectra of $\Lambda_b\pi^\pm$ states, finding peaks at the values of $Q^{(*)\pm} = M(\Sigma^{(*)\pm}) - M(\pi^\pm) - M(\Lambda_b)$ shown in Table 1. These may be combined with the CDF value $M(\Lambda_b) = 5619.7 \pm 1.7 \pm 1.7$ MeV [46] to obtain masses of the $\Sigma_b^{(*)\pm}$ states. Here $Q$ and $Q^*$ denote the averages of $Q^\pm$ and $Q^{*\pm}$, respectively. In this analysis it was assumed that $Q^{*+} - Q^{*-} = Q^+ - Q^-$. This assumption was examined in Ref. [47] and found to be valid to a fraction of an MeV/c$^2$.

A new CDF value for the $\Lambda_b$ lifetime, $\tau(\Lambda_b) = (1.593^{+0.083}_{-0.078} \pm 0.033)$ ps, was reported recently [55]. 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.

The CDF Collaboration has identified events of the form $B_c \rightarrow J/\psi \pi^\pm$, allowing a precise determination of the mass: $M = (6276.5 \pm 4.0 \pm 2.7)$ MeV/c$^2$ [49]. This is in reasonable accord with the latest lattice prediction of $6304 \pm 12^{+18}_{-10}$ MeV [50].
The long-awaited $B_s - \bar{B}_s$ mixing has finally been observed [43, 51]. The CDF value, $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$, constrains $f_{B_s}$ and $|V_{td}/V_{ts}|$, as mentioned earlier.

The Belle Collaboration has observed the decay $B \rightarrow \tau\nu$ [52], leading to $f_B |V_{ub}| = (10.1^{+1.5+1.3}_{-1.4-1.1}) \times 10^{-4}$ GeV. When combined with the value $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ [53], this leads to $f_B = (229^{+38+33}_{-31-34})$ MeV. A recent lattice estimate [54] is $f_B = (216 \pm 22)$ MeV.

5. Charmonium

Remarkable progress has been made in the spectroscopy of charmonium states above charm threshold in the past few years. Fig. 4 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 $D\bar{D}_1$ threshold), other decay modes are being seen. We now discuss some aspects of the recent discoveries.
5.1. Observation of $h_c$

The $h_c(1^P_1)$ state of charmonium has been observed by CLEO \cite{56,57} via $\psi(2S) \rightarrow \pi^0 h_c$ with $h_c \rightarrow \gamma \eta_c$. Hyperfine splittings test the spin-dependence and spatial behavior of the $Q\bar{Q}$ force. While these 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 interaction. Lattice QCD \cite{58} and relativistic potential \cite{59} calculations confirm this expectation. One expects $\eta_c$ not confirmed by Fermilab E835; and a state at $3525\pm 49$ MeV.

Two inclusive analyses with no $(3524\pm 49)\text{MeV}$ production in the direct channel, include a few events seen in CERN ISR Experiment R704; a state 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 \cite{60}.

In the CLEO data, both exclusive and inclusive analyses see a signal near $\langle M(3P_J) \rangle$. The exclusive analysis reconstructs $\eta_c$ in 7 decay modes and sees 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; $B_1(\psi' \rightarrow \pi^0 h_c)B_2(h_c \rightarrow \gamma \eta_c) = (5.3\pm 1.5\pm 1.0) \times 10^{-4}$. Two inclusive analyses with no $\eta_c$ reconstruction yield $M(h_c) = (3524.9\pm 0.7\pm 0.4)$ MeV, $B_1B_2 = (3.5\pm 1.0\pm 0.7) \times 10^{-4}$. Combining exclusive and inclusive results yields $M(h_c) = (3524.4\pm 0.6\pm 0.4)$ MeV, $B_1B_2 = (4.0\pm 0.8\pm 0.7) \times 10^{-4}$. 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 \cite{61} $M(h_c) \geq \langle M(3P_J) \rangle$ and indicating little $P$-wave hyperfine splitting in charmonium. The value of $B_1B_2$ agrees with theoretical estimates of $(10^{-3}\div 0.4)$.

5.2. $\psi''(3770)$

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 $\sigma(e^+e^- \rightarrow \psi'' \rightarrow DD)$, implying significant non-$DD$ decays of $\psi''$ \cite{62}. A new CLEO measurement \cite{63}, $\sigma(\psi'') = (6.38\pm 0.08_{-0.36}^{+0.41}) \text{nb}$, appears very close to the CLEO value $\sigma(DD) = (6.39\pm 0.10_{-0.08}^{+0.17}) \text{nb}$ \cite{64}, leaving little room for non-$DD$ decays. (BES analyses \cite{65} do not exclude a 10–20% non-$DD$ component.)

Some branching ratios for $\psi'' \rightarrow X J/\psi$ \cite{66} are $B(\psi'' \rightarrow \pi^+\pi^- J/\psi) = (0.189\pm 0.020\pm 0.020)\%$, $B(\psi'' \rightarrow \pi^0 J/\psi) = (0.080\pm 0.025\pm 0.016)\%$, $B(\psi'' \rightarrow \eta J/\psi) = (0.087\pm 0.033\pm 0.022)\%$, and $B(\psi'' \rightarrow \eta' J/\psi) < 0.028\%$. The value of $B(\psi''(3770) \rightarrow \pi^+\pi^- J/\psi)$ found by CLEO is a bit above 1/2 that reported by BES \cite{67}. These account for less than 1/2 of the total $\psi''$ decays.

CLEO has reported results on $\psi'' \rightarrow \gamma \chi_{cJ}$ partial widths, based on the exclusive process $\psi'' \rightarrow \gamma \chi_{c1,2} \rightarrow \gamma \gamma J/\psi \rightarrow \gamma \gamma \ell^+\ell^- \rightarrow \chi_{cJ}$ \cite{68} and reconstruction of exclusive $\chi_{cJ}$ decay \cite{69}. The results are shown in Table 2, implying $\sum J B(\psi'' \rightarrow \gamma \chi_{cJ}) = O(1\%)$.

Both CLEO and BES \cite{71}, 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. Several other searches

| Table 2. CLEO results on radiative decays $\psi'' \rightarrow \gamma \chi_{cJ}$. Theoretical predictions of \cite{70} are (a) without and (b) with coupled-channel effects; (c) shows predictions of \cite{62}. |
| --- | --- | --- | --- |
| Mode | Predicted (keV) | CLEO |
| (a) | (b) | (c) |
| $\gamma \chi_{c2}$ | 3.2 | 3.9 | 24.4 $\pm$ | $< 21$ |
| $\gamma \chi_{c1}$ | 183 | 59 | 73 $\pm$ | 75 $\pm$ 18 |
| $\gamma \chi_{c0}$ | 254 | 225 | 523 $\pm$ 12 | 172 $\pm$ 30 |
for \( \psi''(3770) \) → (light hadrons), including \( \eta \), \( K_{L} K_{S} \), and multi-body final states have been performed. Two CLEO analyses \cite{72,73} find no evidence for any light-hadron \( \psi'' \) mode except \( \phi \eta \) above expectations from continuum production.

5.3. The \( \chi_c(3872) \)
Many charmonium states above \( \bar{D}D \) threshold have been seen recently \cite{74,75}. The \( \chi_c(3872) \), discovered by Belle in \( B \) decays \cite{76} and confirmed by BaBar \cite{77} and in hadronic production \cite{78}, decays predominantly into \( J/\psi \pi^+ \pi^- \). Since it lies well above \( \bar{D}D \) 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 \( \langle D^0\bar{D}^{*0} + \bar{D}^0 D^{*0} \rangle / \sqrt{2} \sim c\bar{c}u\bar{u} \) with \( J^{PC} = 1^{++} \). The simultaneous decay of \( \chi_c(3872) \) to \( \rho J/\psi \) and \( \omega J/\psi \) with roughly equal branching ratios is a consequence of this “molecular” assignment.

Analysis of angular distributions \cite{80} in \( X \rightarrow \rho J/\psi, \omega J/\psi \) favors the \( 1^{++} \) assignment \cite{81} (see also \cite{72,73}). An analysis by the CDF Collaboration \cite{82} finds equally good fits of decay angular distributions to \( J^{PC} = 1^{++} \) and \( 2^{-+} \). The latter is disfavored by Belle’s observation \cite{83} of \( X \rightarrow D^0\bar{D}^{*0} \), which would require at least two units of relative orbital angular momentum in the three-body state, very near threshold. Observation of the \( \gamma J/\psi \) mode (\( \sim 14\% \) of \( J/\psi \pi^+ \pi^- \)) \cite{84} confirms the \( C = + \) assignment and suggests a \( c\bar{c} \) admixture in the wave function. BaBar \cite{85} finds \( B[X(3872) \rightarrow \pi^+ \pi^- J/\psi] > 0.042 \) at 90% c.l.

5.4. Charmonium between 3.9 and 4.0 GeV/\( c^2 \)
Belle has reported a candidate for a \( 2^3P_2(\chi_{c2}) \) state in \( \gamma \gamma \) collisions \cite{86}, decaying to \( \bar{D}D \). The angular distribution of \( \bar{D}D \) 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 \( \Gamma_{ee} B(DD) = 0.18 \pm 0.06 \pm 0.03 \) eV, all reasonable for a \( \chi_{c2} \) state.

A charmonium state \( X(3938) \) is produced recoiling against \( J/\psi \) in \( e^+ e^- \rightarrow J/\psi + X \) \cite{87} and is seen decaying to \( \bar{D}D^* + \text{c.c.} \). Since all lower-mass states observed in this recoil process have \( J = 0 \) [these are the \( \eta_c(1S), \chi_{c0} \) and \( \eta_c(2S) \)], 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 \cite{88}. 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 \( \omega \gamma(1S) \) \cite{89}.

5.5. The \( \psi(4260) \)
BaBar has reported a state \( \psi(4260) \) produced in the radiative return reaction \( e^+ e^- \rightarrow \gamma \pi^+ \pi^- J/\psi \) and seen in the \( \pi^+ \pi^- J/\psi \) spectrum \cite{90}. Its mass is consistent with being a 4S level \cite{91} since it lies about 230 MeV above the 3S candidate (to be compared with a similar 4S-3S spacing in the \( \Upsilon \) system). The level spacings of charmonium and bottomonium 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 \cite{92}. Other interpretations of \( \psi(4260) \) include a \( c\bar{c}s\bar{s} \) state \cite{93} and a hybrid \( c\bar{c}g \) state \cite{94}, for which it lies in the expected mass range.

The CLEO Collaboration has confirmed the \( \psi(4260) \), both in a direct scan \cite{95} and in radiative return \cite{90}. Signals are seen for \( \psi(4260) \rightarrow \pi^+ \pi^- J/\psi \) (11\%), \( \pi^0 \pi^0 J/\psi \) (5.1\%), and \( K^+ K^- J/\psi \) (3.7\%). There are also weak signals for \( \psi(4160) \rightarrow \pi^+ \pi^- J/\psi \) (3.6\%) and \( \pi^0 \pi^0 J/\psi \) (2.6\%), consistent with the \( \psi(4260) \) tail, and for \( \psi(4040) \rightarrow \pi^+ \pi^- J/\psi \) (3.3\%). Both CLEO and Belle \cite{97} see the state at slightly higher mass than BaBar.

The hybrid interpretation of \( \psi(4260) \) deserves further attention. One consequence is a predicted decay to \( \bar{D}D_1 + \text{c.c.} \), where \( D_1 \) is a P-wave \( c\bar{q} \) pair. Now, \( \bar{D}D_1 \) threshold is 4287 MeV/\( c^2 \) if we consider the lightest \( D_1 \) to be the state noted in Ref. \cite{27} at 2422 MeV/\( c^2 \). In
Figure 5. $b\bar{b}$ levels and some decays. Electric dipole (E1) transitions $S\leftrightarrow P \leftrightarrow D$ are not shown.

dthis case the $Y(4260)$ would be a $D\bar{D}_1+\text{c.c. bound state}$. 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 $D\bar{D}_1$ threshold, which may be the first S-wave meson pair accessible in $c\bar{c}$ fragmentation [98]. The $D^*\bar{D}_1$ mode could also be either another decay channel of $Y(4260)$ or represent a separate resonance with slightly greater mass and width.

6. Bottomonium

Some properties and decays of the $\Upsilon (b\bar{b})$ levels are summarized in Fig. 5. Masses are in agreement with unquenched lattice QCD calculations [99]. Direct photons have been observed in 1S, 2S, and 3S decays, implying estimates of the strong fine-structure constant consistent with others [100]. The transitions $\chi_b(2P) \rightarrow \pi\pi\chi_b(1P)$ have been seen [101, 102]. BaBar has measured the partial widths $\Gamma[\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)] = 1.8 \pm 0.4 \text{ keV}$ and $\Gamma[\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)] = 2.7\pm 0.8 \text{ keV}$ [103], while Belle has seen $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, with a branching ratio $\mathcal{B} = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$ [104].

6.1. Remeasurements by the CLEO Collaboration

New values of $\mathcal{B}[\Upsilon(1S, 2S, 3S) \rightarrow \mu^+\mu^-] = (2.49 \pm 0.02 \pm 0.07, 2.03 \pm 0.03 \pm 0.08, 2.39 \pm 0.07 \pm 0.10)\%$ [105], when combined with new measurements $\Gamma_{ee}(1S, 2S, 3S) = (1.252 \pm 0.004 \pm 0.019, 0.581 \pm 0.004 \pm 0.009, 0.413 \pm 0.004 \pm 0.006) \text{ keV}$ and previous data, imply total widths [27] $\Gamma_{\text{tot}}(1S, 2S, 3S) = (54.02 \pm 1.25, 31.98 \pm 2.63, 20.32 \pm 1.85) \text{ keV}$. The values of $\Gamma_{\text{tot}}(2S, 3S)$ are significantly below previous world averages [106], leading to changes in comparisons of predicted and observed transition rates. As one example, the study of $\Upsilon(2S, 3S) \rightarrow \gamma X$ decays [107] has provided new branching ratios for E1 transitions to $\chi_bJ(1P)$, $\chi_bJ(2P)$ states. These may be combined with the new total widths to obtain updated partial decay widths [Table 5].
Table 3. Comparison of observed (a) and predicted (b) partial widths for $2S \to 1P_J$ and $3S \to 2P_J$ transitions in $b\bar{b}$ systems.

|          | $\Gamma$ (keV), $2S \to 1P_J$ transitions | $\Gamma$ (keV), $3S \to 2P_J$ transitions |
|----------|------------------------------------------|------------------------------------------|
|          | $J = 0$ $J = 1$ $J = 2$                  | $J = 0$ $J = 1$ $J = 2$                  |
| (a)      | 1.20±0.18 2.22±0.23 2.32±0.23            | 1.38±0.19 2.95±0.30 3.21±0.33            |
| (b)      | 1.39 2.18 2.14                           | 1.65 2.52 2.78                           |

(a)], which may be compared with one set of non-relativistic predictions [108] [line (b)]. The suppression of transitions to $J = 0$ states by 10–20% with respect to non-relativistic expectations agrees with relativistic predictions [109]. The partial width for $\Upsilon(3S) \to \gamma^3P_0$ is found to be 61±23 eV, about nine times the highly-suppressed value predicted in Ref. [108]. That prediction is very sensitive to details of wave functions; the discrepancy indicates the importance of relativistic distortions.

6.2. $b\bar{b}$ 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 $1S, 2S, 3S$ hyperfine splittings to be approximately 60, 30, 20 MeV/$c^2$, respectively [110]. The lowest $P$-wave singlet state (“$h_b$”) is expected to be near $\langle M(1^3P_J) \rangle \approx 9900$ MeV/$c^2$ [111].

Several searches have been performed or are under way in $1S, 2S, 3S$ CLEO data. One can search for the allowed M1 transition in $\Upsilon(1S) \to \gamma \eta b(1S)$ 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 $\Upsilon(n'S) \to \gamma \eta b(nS)$ ($n \neq n'$) decays. These searches already exclude many models. The strongest upper limit obtained is for $n' = 3, n = 1$: $B \leq 4.3 \times 10^{-4}$ (90% c.l.). $\eta b$ searches using sequential processes $\Upsilon(3S) \to \pi^0 \eta b(1^1P_1) \to \pi^0 \gamma \eta b(1S)$ and $\Upsilon(3S) \to \gamma \chi_{b0} \to \gamma \eta b(1S)$ (the latter suggested in Ref. [112]) 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 [113] is $\mathcal{O}(10^{-3})$], with a possible $h_b \to \gamma \eta b$ transition expected to have a 40% branching ratio [111].

7. Future prospects

CLEO and BES-III will make new contributions to heavy quark spectroscopy. CLEO will focus on center-of-mass energies 3770 and 4170 MeV, to obtain about 750 pb$^{-1}$ at each energy. Goals include the best possible determination of $f_D$ and $f_{Ds}$, measurements of form factors for semileptonic $D$ and $Ds$ decays which will provide incisive tests for lattice gauge theories, and measurement of the CKM factors $V_{cd}$ and $V_{cs}$ with unprecedented precision. CLEO collected over 26 million $\psi(2S)$ (about 8 times the current sample) this past summer and looks forward to fruitful analyses of these data. CLEO-c running will end at the end of March 2008; BES-III will take over, and PANDA (a proposed detector in Germany) is anticipated to begin running in 2014.

Belle has taken 2.9 fb$^{-1}$ of data at $\Upsilon(3S)$. They have been concerned primarily with “invisible” decays of the $\Upsilon(1S)$ [also the subject of a CLEO search], tagged via $\Upsilon(3S) \to \pi^+ \pi^- \Upsilon(1S)$. This sample is also potentially valuable for spectroscopy. CLEO has (1.1, 1.2, 1.2)
fb$^{-1}$ at 1S, 2S, 3S. Both BaBar and Belle have shown interest in hadron spectroscopy; they are well-positioned to study it. There have been useful contributions from CDF and D0 as well.

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 the $\psi''(3770)$ have been important in confirming its interpretation as a D-wave $c\bar{c}$ state with some S-wave admixture. We are continuing to learn about properties of QCD in the strong-coupling regime through 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. Understanding the mystery of electroweak symmetry breaking or the very structure of quarks and leptons may require related techniques. These insights 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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