The XYZ's of $c\bar{c}$: Hints of Exotic New Mesons

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I discuss the nature of the new charm and charmonium like states observed in the last few years and measurements that can test these assignments. In particular it appears that the $X(3943)$ is the $\eta_c''(3^1S_0)$ which can be tested by looking for it in $\gamma\gamma \to D\bar{D}^*$, the $Y(3943)$ is the $\chi_{c1}'(2^3P_1)$ which can be tested by looking for it in $D\bar{D}$ and $D\bar{D}^*$, the $Z(3930)$ is the $\chi_{c2}'(2^3P_2)$ which can be confirmed by looking for it in $D\bar{D}^*$. If the $X(3872)$ is confirmed to have $J^{PC} = 1^{++}$ it is almost certainly a multiquark state while if its J^{PC} is found to be 2^{-+} is is likely the 1^1D_2 state. The $Y(4260)$ appears to be an extra 1^{--} which is most easily explained as a charmonium hybrid. This can be tested by looking the DD_1 final state.

1. Introduction

The last few years have seen a phenomenal resurgence in charm and quarkonium spectroscopy. It began in July 2002 when CLEO presented evidence for a D-wave $b\bar{b}$ meson [1]. This was the first new quarkonium state to be observed in almost twenty years. Since then eight new charmonium like states have been observed [2–14] plus the B_c [15–17], the puzzling $D_{sJ}^{(*)}$ states [18–21], and the broad D P-wave states [22–24]. This collection of states have in some cases confirmed quark model and Lattice QCD calculations while in other cases challenged our understanding. In other words it's an exciting time to be a spectroscopist! In this mini-review I survey these new states, concentrating on conventional interpretations and suggesting non-quarkonium explanations when all else fails. My talk is complemented by Voloshin's talk which concentrates on multiquark descriptions of some of these states [25].

This mini-review starts with some brief remarks about conventional meson spectroscopy, radiative transitions, and strong decays along with comments about hybrid mesons – states with an excited gluonic degree of freedom. It is followed by a brief discussion of the charm-strange mesons and broad P-wave charm mesons primarily focusing on some recent experimental results and how we can test the identity of these states. The bulk of this review concentrates on the various new charmonium like states; the X, Y, Z's of the title. In the final section I summarize my conclusions about these states and suggest experimental tests of the interpretations. Some of these topics have recently been reviewed by Swanson [26].

2. General Remarks on Spectroscopy

This section is intended to be a reminder of the template we are using to test for "exotic" states. We use the predictions of a specfic model [27] as our template and briefly describe some details of this approach. An extensive review of quarkonium physics, including other calculations and detailed references, is given in Ref. [28].

In quark potential models, conventional meson quantum numbers are characterized by the J^{PC} given by $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$ where S is the total spin of the $q\bar{q}$ pair and the total angular momentum J is found by adding S to L, the orbital angular momentum of the quark antiquark pair. To obtain the quarkonium spectrum one starts with a potential and solves the eigenvalue equation, Schrodinger equation or otherwise, for orbital and radial excitations. The potential typically consists of a short distance Coulomb potential expected from one-gluon-exchange and a linear confining potential at large separation. This phenomenological potential is in good agreement with the static quarkonium potential calculated using Lattice QCD.

In addition to the spin-independent potential there are spin dependent interactions which are $(v/c)^2$ corrections. They are found by assuming that the short distance one-gluon-exchange is a Lorentz vector interaction and the confinement piece is Lorentz scalar. This gives rise to multiplet splittings. For example, the $J/\psi - \eta_c$ splitting is attributed to a short distance $\vec{S}_q \cdot \vec{S}_{\bar{q}}$ contact interaction arising from the one-gluon-exchange while the splitting of the P-wave χ_c states is due to spin orbit interactions arising from one-gluon-exchange and the relativistic Thomas precession piece in addition to a tensor spin-spin interaction. The recent measurement of the h_c mass is an important validation of this picture.

The properties of meson states can be further tested by calculating electromagnetic and strong decays (and for that matter weak decays of stable states) and comparing them to experiment. The calculation of radiative transitions are straightforward and are described in many places [29]. For the strong decays we rely on the $^3P_0$ decay model which describes most strong decays reasonably well [30–35]. Decays of charmonium states up to $\sim$ 4.6 GeV were calculated by Barnes Godfrey and Swanson [36] with similar results obtained by Eichten Lane and Quigg [37]. These results can be used to test the properties of a newly discovered state to see if and where it fits into the expected charmonium spectroscopy.

In addition to the conventional quarkonium states other hadron states are expected. Multiquark states have a larger quark content than the conventional $q\bar{q}$. The details are rather complicated and has spawned a subfield in the literature studying the different predictions for various possible configurations. For example, in one extreme these multiquark states consist of tightly bound $q^2\bar{q}^2$ and are referred to as "tetraquarks" while the other extreme consists of loosely bound mesons such as $D\bar{D}$ and are referred to as molecules. I refer you to Voloshin's contribution [25].

The other type of exotic quarkonium state are the so-called hybrid mesons which have an excited gluonic degree of freedom. These are described by many different models and calculational schemes [38]. The picture I prefer is analogous to molecular physics where the quarks move in adiabatic potentials arising from the gluons which can be compared to nuclei moving in the adiabatic potentials arising from the electrons in molecules. The lowest adiabatic surface leads to the conventional quarkonium spectrum while the excited adiabatic surfaces are found by putting the quarks into more complicated colour configurations. The adiabatic potentials have been calculated using Lattice QCD [39, 40]. In the flux tube model [41] the lowest excited adiabatic surface corresponds to transverse excitations of the flux tube and leads to a doubly degenerate octet of the lowest mass hybrids with quantum numbers $J^{PC} = 0^{+-}$, 0^{-+}, 1^{+-}, 1^{-+}, 2^{+-}, 2^{-+}, 1^{++} and 1^{--}. The 0^{+-}, 1^{-+}, 2^{+-} quantum numbers are not possible in the quark model and are referred to as exotic quantum numbers. If observed, they would unambiguously signal the existence of unconventional states. Lattice QCD and most models predict the lowest charmonium hybrid state to be roughly 4.2 GeV in mass.

Charmonium hybrids can decay via electromagnetic transitions, hadronic transitions such as $\psi_g \to J/\psi + \pi\pi$, and to open charm final states like $\psi_g \to D^{(*,**)}\bar{D}^{(*,**)}$. The partial widths have been calculated using many different models. There are some general properties that seem to be supported by most models and by recent lattice QCD calculations. Nevertheless there are no experimental results against which to test these calculations so one should take these predictions with a grain of salt. Two important decay modes are:

1. $\psi_g \to D^{(*,**)}\bar{D}^{(*,**)}$. Most calculations predict that the ψ_g should decay to a P-wave plus an S-wave meson. In other words $D(L = 0) + D^{**}(L = 1)$ final states should dominate with vanishing partial widths for decays to $D\bar{D}$ and a small partial width to $D\bar{D}^*$.

2. $\psi_g \to (c\bar{c})(gg) \to (c\bar{c}) + (\pi\pi,\ \eta \ldots)$ This mode offers the cleanest signature. If the total width is small it could have a significant branching fraction. A recent lattice QCD calculation finds that these decays are potentially quite large, $\mathcal{O}(10 \text{ MeV})$ although it should be noted that the calculation was for $(b\bar{b})_g \to \chi_b S$ where S is a light scalar meson[42].

3. Some Other New States

Before proceeding to the puzzles I was asked to review I want to mention several other new states which have added to our understanding of meson spectroscopy.

$\Upsilon(1D)$ This state was first announced by CLEO at the 2002 ICHEP conference [1]. It's mass of $M(\Upsilon) = 10161.1 \pm 0.6(stat) \pm 1.6(syst)$ MeV is in good agreement with potential models [27] and lattice QCD calculations [43].

B_c While observed previously [15, 16] the CDF collaboration recently presented a precise mass measurement which could confront theoretical predictions [17]. The observed mass of $M(B_c) = 6287.0 \pm 4.8(stat) \pm 1.1(syst)$ MeV compares favourably to the lattice QCD result of 6304 ± 12 MeV [44] and the quark potential model result of 6271 MeV [27, 45].

η_c' This state was recently observed by Belle [2] and CLEO [3]. The combined mass of $M(\eta_c') = 3637.4 \pm 4.4$ MeV is slightly higher than the quark model prediction of 3623 MeV [27, 36] so that the quark model slightly overestimates the $2^3S_1 - 2^1S_0$ splitting. Eichten Lane and Quigg [37] studied the coupled channel contributions to $c\bar{c}$ states and found that this reduces the splitting, bringing it into better agreement with experiment.

h_c This state was recently observed by the CLEO collaboration [4]. Its mass of $M(h_c) = 3524.4 \pm 0.6(stat) \pm 0.4(syst)$ MeV gives the $^3P_J - ^1P_1$ splitting of $M(^3P_J) - M(^1P_1) = 1.0 \pm 0.6(stat) \pm 0.4(syst)$ MeV which implies a very short range contact interaction supporting the Lorentz-vector 1-gluon-exchange plus Lorentz-scalar linear confining potential. The predictions for this splitting had a very large variation so this measurement is a useful constraint on models [46, 47].

Taken together these results provide an important test of quarkonium spectroscopy calculations and help calibrate the reliability of the predictions.

4. The $D_{sJ}(2317)$ and $D_{sJ}(2460)$

The $D_{sJ}(2317)$ was first observed by Babar [18] and the $D_{sJ}(2460)$ by CLEO [19]. Both were subsequently seen and studied by Belle [20]. Their properties are consistent with $J^P = 0^+$ and 1^+ respectively. Two broad P-wave charm-strange mesons were expected with the $J^P = 0^+$ state decaying to DK and the 1^+ to D^*K [48]. But both states are very narrow with the $D_{sJ}(2317)$ below the DK threshold and the $D_{sJ}(2460)$ below the D^*K threshold. This unexpected behavior created a major theory industry describing the D_{sJ} states as multiquark states, molecular states, $D\pi$ atom, and as conventional $c\bar{s}$ states but with some improvement needed in the models [49]. What caught everybody's attention was how narrow these states were. The problem is in the mass predictions. Once the masses are fixed the narrow widths follow [49–52].

The phenomenology of these states has been discussed elsewhere [49–52] so I will restrict myself to comments on some new measurements by Babar relating to radiative transitions [53]. At the outset it was pointed out that for states this narrow radiative transitions are expected to have large branching ratios so measurement of radiative transitions is an important probe of their internal structure [50–52]. Babar obtained the following results [53]:

$$\mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^{*-}\pi^0) = 0.51 \pm 0.11 \pm 0.09$$
$$\mathcal{B}(D_{sJ}(2460)^- \rightarrow D_s^{-}\gamma) = 0.15 \pm 0.03 \pm 0.02$$
$$\mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^{+}\pi^+\pi^-) = 0.04 \pm 0.01 \text{ (stat only)}$$

Summing the BR's there is a missing $(30 \pm 15)\%$. Where did it go? Recall that because C is no longer a good quantum number for unequal mass quark and antiquark the physical $L = 1$ J=1 states are a linear combination of $^3P_1$ and $^1P_1$ [51]:

$$D_{s1}^{1/2} = -^1P_1 \sin\theta + ^3P_1 \cos\theta \qquad (1)$$

So we expect the decay $D_{sJ}(2460)^- \rightarrow D_s^{*-}\gamma$ to occur and the measurement of its BR can be used to determine the $^3P_1 -^1 P_1$ mixing angle via [54, 55]

$$\frac{\Gamma(^3P_1 \rightarrow ^3S_1 + \gamma)}{\Gamma(^1P_1 \rightarrow ^1S_0 + \gamma)} = \frac{\omega_t^3 |\langle ^3S_1|r|^3P_1\rangle|^2 \cos^2\theta}{\omega_s^3 |\langle ^1S_0|r|^1P_1\rangle|^2 \sin^2\theta} \qquad (2)$$

where ω_t and ω_s are the photon energies for the two transitions and $\langle ^{3,1}S_{1,0}|r|^{3,1}P_1\rangle$ are the $E1$ dipole matrix elements. The 1/2 superscript refers to the total angular of the light quark in the heavy quark limit.

To summarize, the D_{sJ} states appear to be the conventional $L = 1$ $c\bar{s}$ states with their masses shifted due to strong S-wave coupling to $DK^{(*)}$ and their nearness to the $DK^{(*)}$ thresholds.

While almost all the theoretical effort has concentrated on the D_{sJ} states it is important to remember that the non-strange partners can also provide information that can test these models [48, 54]. Specifically, quark model predictions are in good agreement with the masses and widths of the charm P-wave mesons. Predictions for the radiative transitions have also been calculated. While the $j_q = 1/2$ are too broad to be able to measure the radiative widths, it should be possible to measure the branching ratios of the radiative transitions of the narrow states. In particular, measuring the BR's of the $D_1^{3/2}$ to $D\gamma$ and $D^*\gamma$ is a means of measuring the $^3P_1 -^1 P_1$ mixing angle [54].

5. $D_{sJ}(2632)$

This state was observed by the SELEX collaboration in hadroproduction in $D_s^+\eta$ and D^0K^+ final states [21]. It's measured mass is $M = 2632.6 \pm 1.6$ MeV but with the odd properties of a narrow width of $\Gamma < 17$ MeV at 90% C.L. and the ratio of partial widths of $\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$. It has not been seen by other high statistics experiments [56] so it's existence is in doubt.

For the sake of argument let's investigate what it might be [57]. The possibilities mentioned in the literature are a $2^3S_1(c\bar{s})$ state, a $c\bar{s}$ hybrid and multiquark assignments [58–60]. The lowest $c\bar{s}$ hybrid is expected to be about 3170 MeV so it is unlikely that we can identify the $D_{sJ}(2632)$ as a hybrid. The most plausible conventional $c\bar{s}$ states are the 2^3S_1 with a predicted mass of 2730 MeV and the 1^3D_1 with mass 2900 MeV [57]. One could attribute the discrepancy with the $D_{sJ}(2632)$ mass to mixing with the 2-meson continuum.

If we assume the $D_{sJ}(2632)$ is the $2^3S_1(c\bar{s})$ state we can calculate the open-flavour decay widths and find

$$\Gamma(D^*K) > \Gamma(DK) >> \Gamma(D_s\eta) \qquad (3)$$

The total width is predicted to be $\Gamma(D_{sJ}(2632) = 36$ MeV and $\Gamma(DK)/\Gamma(D_s\eta) \simeq 9$. This should be compared to the SELEX value of $\Gamma(DK)/\Gamma(D_s\eta) = 0.32 \pm 0.12$. Clearly theory and experiment are inconsistent. It is possible to tune the model to obtain agreement but this fine tuning seems highly unlikely.

We conclude that the SELEX $D_{sJ}(2632)$ needs confirmation. Nevertheless, experiment should be able to observe the $2^3S_1(c\bar{s})$ in B-meson decays with the largest decay mode predicted to be the D^*K final state. The $1^3D_1(c\bar{s})$ should also exist about 200 MeV higher in mass.

6. The $X(3943)$, $Y(3943)$, and $Z(3931)$

Three new $c\bar{c}$-like states have been observed with $C = +$. Their masses are consistent with the $2P$ $c\bar{c}$ multiplet and the $3^1S_0(c\bar{c})$ state. Before turning to exotic interpretations we need to determine if they are conventional $c\bar{c}$ states.

6.1. $X(3943)$

The $X(3943)$ was observed by the Belle collaboration recoiling against J/ψ in e^+e^- collisions [5]. The mass and width were measured to be $M = 3943 \pm 6 \pm 6$ MeV and $\Gamma = 15.4 \pm 10.1$ MeV. They find $BR(X \to D\bar{D}^*) = 96^{+45}_{-32} \pm 22\%$, $BR(X \to D\bar{D}) < 41\%$ (90% CL), and $BR(X \to \omega J/\psi) < 26\%$ (90% CL). The decay to $D\bar{D}^*$ but not $D\bar{D}$ suggests it is an unnatural parity state.

Belle speculates that the $X(3943)$ is the $3^1S_0(c\bar{c})$ given the $3^3S_1(c\bar{c})$ $\psi(4040)$. It's mass is roughly correct and the η_c and η_c' are also produced in double charm production. This was also discussed by Eichten Lane and Quigg [37]. The predicted width for a 3^1S_0 with a mass of 3943 MeV is ~ 50 MeV [37] which is not in too bad agreement with the measured $X(3943)$ width. The identification of the $\psi(4040)$ as the $3^3S_1(c\bar{c})$ implies a hyperfine splitting of 88 MeV with the $X(3943)$. This is larger than the $2S$ hyperfine splitting and larger than predicted by potential models. The discrepancy could be due to several possibilities; difficulty in fitting the true pole position of the 3^3S_1 state or strong threshold effects due to the nearby thresholds with S-wave and P-wave charm mesons.

The dominant $D\bar{D}^*$ final states hints at the possibility that the $X(3943)$ is the $2^3P_1(c\bar{c})$ χ_1' state. It is natural to try the $2P(c\bar{c})$ since the 2^3P_J states are predicted to lie in the 3920-3980 MeV mass region and the widths are predicted to be in the range $\Gamma(2^3P_J) = 30 - 165$ MeV [36]. The dominant $D\bar{D}^*$ mode suggests that the $X(3943)$ is the $2^3P_1(c\bar{c})$ state. The problems with this interpretation are that there is no evidence for the $1^3P_1(c\bar{c})$ state in the same data and the predicted width of the $2^3P_1(c\bar{c})$ is 135 MeV (assuming $M(2^3P_1(c\bar{c})) = 3943$ MeV) [61]. Finally, there is another candidate for the $1^3P_1(c\bar{c})$ state, the $Y(3943)$.

To conclude, the most likely interpretation of the $X(3943)$ is that it is the $3^1S_0(c\bar{c})$ η_c'' state. A test of this assignment is a search for this state in $\gamma\gamma \to D\bar{D}^*$.

6.2. $Y(3940)$

The $Y(3940)$ is seen by Belle in the $\omega J/\psi$ subsystem in the decay $B \to K\pi\pi\pi J/\psi$ [6]. The reported mass and width are $M = 3943 \pm 11 \pm 13$ MeV and $\Gamma = 87 \pm 22 \pm 26$ MeV. It is not seen in $Y \to D\bar{D}$ or $D\bar{D}^*$. The mass and width suggest a radially excited P-wave charmonium state. But the $\omega J/\psi$ decay mode is peculiar. The combined BR is $\mathcal{B}(B \to KY) \cdot \mathcal{B}(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$. One expects that $\mathcal{B}(B \to K\chi_{cJ}') < \mathcal{B}(B \to K\chi_{cJ}) = 4 \times 10^{-4}$. This implies that $\mathcal{B}(Y \to \omega J/\psi) > 12\%$ which is unusual for a $c\bar{c}$ state above open charm threshold.

This large width to $\omega J/\psi$ led Belle to suggest that the $Y(3943)$ might be a charmoniun hybrid. The problem with this interpretation is that the Y mass is 500 MeV below the lattice gauge theory estimate making the hybrid assignment unlikely.

If we identify the $Y(3940)$ with the χ_{c1}' $2^3P_1(c\bar{c})$ state we expect $D\bar{D}^*$ to be the dominant decay mode with a predicted width of 135 MeV [61] which is consistent with that of the $Y(3940)$ within the theoretical and experimental uncertainties. Furthermore, the χ_{c1} is also seen in B-decays.

The decay $1^{++} \to \omega J/\psi$ is unusual. However, the corresponding decay $\chi_{b1}' \to \omega\Upsilon(1S)$ has also been seen [62]. One possible explanation for this unusual decay mode is that rescattering through $D\bar{D}^*$ is responsible; $1^{++} \to D\bar{D}^* \to \omega J/\psi$. Another contributing factor might mixing with the possible molecular state tentatively identified with the $X(3872)$.

We therefore tentatively identify the $Y(3940)$ as the χ_{c1}' $2^3P_1(c\bar{c})$ state. This can be tested by searching for the $D\bar{D}$ and $D\bar{D}^*$ final states and by studying their the angular distributions (χ_{c1}' can only decay to $D\bar{D}^*$).

6.3. $Z(3930)$

The $Z(3930)$ was observed by Belle in $\gamma\gamma \to D\bar{D}$ with mass and width $M = 3929 \pm 5 \pm 2$ MeV and $\Gamma = 29 \pm 10 \pm 2$ MeV [7]. The two photon width is measured to be $\Gamma_{\gamma\gamma} \cdot \mathcal{B}_{D\bar{D}} = 0.18 \pm 0.05 \pm 0.03$ keV. The $D\bar{D}$ angular distribution is consistent with $J = 2$. It is below D^*D^* threshold.

It is the obvious candidate for the χ_{c2}' $2^3P_2(c\bar{c})$ state. (The χ_{c1}' cannot decay to $D\bar{D}$.) The predicted mass of the χ_{c2}' is 3972 MeV. The predicted partial widths and total width assuming $M(2^3P_2(c\bar{c})) = 3930$ MeV are $\Gamma(\chi_{c2}' \to D\bar{D}) = 21.5$ MeV, $\Gamma(\chi_{c2}' \to D\bar{D}^*) = 7.1$ MeV and $\Gamma_{total}(\chi_{c2}') = 28.6$ MeV [37, 63] in good agreement with the experimental measurement. Furthermore using $\Gamma(\chi_{c2}' \to \gamma\gamma) = 0.67$ keV [64] times $\mathcal{B}(\chi_{c2}' \to D\bar{D}) = 70\%$ implies $\Gamma_{\gamma\gamma} \cdot \mathcal{B}_{D\bar{D}} = 0.47$ keV which is within a factor of 2 of the observed number, fairly good agreement considering the typical reliability of 2-photon partial width predictions.

There is no reason to believe that the $Z(3930)$ is not the χ_{c2}'. However, for the sake of argument, let us consider the alternative possibility that it is the χ_{c0}' (which is not supported by the angular distributions). The χ_{c0}' only decays to $D\bar{D}$ while the χ_{c2}' decays to both $D\bar{D}$ and $D\bar{D}^*$ in the ratio of $D\bar{D}^*/D\bar{D} \simeq 1/3$. Thus, the χ_{c2}' interpretation could be confirmed by observation of the $D\bar{D}^*$ final state. Finally we note that both the χ_{c2}' and χ_{c0}' undergo radiative transitions to ψ' with partial widths $\Gamma(\chi_{c2}' \to \gamma\psi') \simeq 200$ keV and $\Gamma(\chi_{c0}' \to \gamma\psi') \simeq 130$ keV [36]. Eichten Lane and

Quigg find these decays are suppressed due to coupled channel effects [37].

6.4. Production of χ'_{cJ} via Radiative Transitions

It is potentially possible to observe all three $2^3P_J(c\bar{c})$ states in radiative decays of the $\psi(4040)$ and $\psi(4160)$ to $\gamma D\bar{D}$ and $\gamma D\bar{D}^*$ [36]. The partial widths of $\psi(3S) \to 2^3P_J\gamma$ are 14, 39, and 54 keV for the 2^3P_2, 2^3P_1, and 2^3P_0 respectively. Thus, all three $E1$ branching ratios of $\psi(4040) \to \chi'_{cJ}\gamma$ are $\sim 0.5 \times 10^{-3}$. Observing these transitions would further test whether the $X(3943)$, $Y(3940)$, and $Z(3930)$ are in fact the $2P(c\bar{c})$ states

7. $X(3872)$

The $X(3872)$ was first observed by Belle [11] and subsequently confirmed by CDF [12], D0 [13], and Babar [14]. The mass of this state is $M = 3872.0 \pm 0.6 \pm 0.5$ MeV and the width is $\Gamma < 2.3$ MeV (90 % C.L.) which is consistent with detector resolution.

This stimulated considerable speculation with a number of interpretations proposed in the literature; $D^0\bar{D}^{*0}$ molecule, charmonium hybrid, glueball, and a conventional 2^3P_J or 1^3D_2 state.

I'll briefly examine the possible charmonium interpretations [36, 37, 65, 66]. Only the $1D$ and $2P$ multiplets are nearby in mass. The 1^3D_1, 1^3D_2, 1^3D_3 and 2^1P_1 have $C = -$ (although the $\psi(3770)$ is identified with the 1^3D_1) and the 1^1D_2, 2^3P_0, 2^3P_1, and 2^3P_2 have $C = +$. The observation of $X(3872) \to \gamma J/\psi$ by Belle [67] and Babar [68] implies $C = +$. An angular distribution analysis by the Belle collaboration favours $J^{PC} = 1^{++}$ [69] although a higher statistics analysis by CDF cannot distinguish between $J^{PC} = 1^{++}$ or 2^{-+} [70] . Assuming it is 1^{++} the only surviving candidate is the 2^3P_1 but as we have just seen the identification of the $Z(3931)$ with the 2^3P_2 imples a $2P$ mass of ~ 3940 MeV which is inconsistent with the 2^3P_1 interpretation. This leads to the conclusion that the $X(3872)$ is a $D^0\bar{D}^{0*}$ molecule or "tetraquark" state. This is discussed in detail by Voloshin [25]. However, as just mentioned, the 2^{-+} is not totally ruled out and the predicted 2^1D_2 mass is not too far from the observed $X(3872)$ mass. A test of these hypothesis would be the observation of radiative transitions involving the $X(3872)$ [65].

8. $Y(4260)$

Perhaps the most intriguing recently discovered state is the $Y(4260)$ discovered by Babar as an enhancement in the $\pi\pi J/\psi$ subsystem in $e^+e^- \to \gamma_{ISR}J/\psi\pi\pi$ [8]. The measured mass and width are $M = 4259 \pm 8 \pm 4$ MeV and $\Gamma = 88 \pm 23 \pm 5$ MeV. The leptonic width times $BR(Y \to J/\psi\pi^+\pi^-)$ was measured as $\Gamma_{ee} \times BR(Y \to J/\psi\pi^+\pi^-) = 5.5 \pm 1.0 \pm 0.8$ eV. Further evidence was seen by Babar in $B \to K(\pi^+\pi^- J/\psi)$ [9] and by CLEO in $\sigma(e^+e^- \to \pi\pi J/\psi)$ [10].

The first unaccounted for $1^{--}(c\bar{c})$ state is the $\psi(3^3D_1)$. Quark models estimate it's mass to be $M(3^3D_1) \simeq 4500$ MeV which is much too heavy to be the $Y(4260)$. The $Y(4260)$ therefore represents an overpopulation of the expected 1^{--} states. The absence of open charm production also argues against it being a conventional $c\bar{c}$ state. A number of explanations have appeared in the literature: $\psi(4S)$ [71], tetraquark [72], and $c\bar{c}$ hybrid [73–75].

Let us consider the possibility that the $Y(4260)$ is a charmonium hybrid. The flux tube model predicts that the lowest $c\bar{c}$ hybrid mass is ~ 4200 MeV [38] with lattice gauge theory having similar expectations [76]. Models of hybrids typically expect the wavefunction at the origin to vanish implying a small e^+e^- width in agreement with the observed value. LGT found that the $b\bar{b}$ hybrids have large couplings to closed flavour models [42] which is similar to the Babar observation of $Y \to J/\psi\pi^+\pi^-$; the branching ratio of $\mathcal{B}(Y \to J/\psi\pi^+\pi^-) > 8.8\%$ combined with the observed width implies that $\Gamma(Y \to J/\psi\pi^+\pi^-) > 7.7 \pm 2.1$ MeV. This is much larger than the typical charmonium transitions of, for example, $\Gamma(\psi(3770) \to J/\psi\pi^+\pi^-) \sim 80$ keV. And the Y is seen in this mode while the conventional states $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ are not.

With this circumstantial evidence for the $Y(4260)$ assignment what measurements can be used to test this hypothesis? LGT suggests that we search for other closed charm modes with $J^{PC} = 1^{--}$; $J/\psi\eta$, $J/\psi\eta'$, $\chi_{cJ}\omega \ldots$ Models of hybrid decays predict that the dominant hybrid charmonium open-charm decay modes will be a meson pair with an S-wave (D, D^*, D_s, D_s^*) and a P-wave (D_J, D_{sJ}) in the final state [74]. The dominant decay mode is expected to be $DD_1(2420)$. However the $D_1(2420)$ has a width of ~ 300 MeV and decays to $D^*\pi$. This suggest the search for $Y(4260)$ in the $DD^*\pi$ final state. Evidence for a large $DD_1(2420)$ signal would be strong evidence for the hybrid interpretation. Having said this, it should be pointed out that models of hybrids have yet to be tested against experiment so we should be cautious. For example, if other modes that were expected to be suppressed like DD^* and $D_sD_s^*$ are found to be comparable to the $J/\psi\pi^+\pi^-$ mode, the $Y(4260)$ may still be a hybrid, but the decay models are simply not reliable.

Another test is to search for partner states. It is expected that the low lying hybrids consist of eight states in the multiplet with masses in the 4.0 to 4.5 GeV mass range with LGT preferring the higher side of the range [77]. Start by confirming that no $c\bar{c}$ states with the same J^{PC} are expected at this mass. Then identify J^{PC} partners of the hybrid candidate which are nearby in mass. It would be most convincing if some of these partners were found, especially the J^{PC} exotics. In the flux-tube model the exotic states have $J^{PC} = 0^{+-}$, 1^{-+}, and 2^{+-} while the non-exotic low lying hybrids have 0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, and 1^{--}.

9. Summary

In the last few years there have been many new results representing considerable progress in our understanding of the spectroscopy involving charm quarks. In some cases they have verified our models, in other cases they hint towards filling in missing multiplets, but most intriguing, in some cases they hint at non-$c\bar{c}$ states that could be our first evidence of qualitatively new types of hadronic matter. I summarize the states I discussed in the following table:

Table I Summary of the new charm and charmonium states discussed in this mini-review.

State	Interpretation and Tests
$D_{sJ}(2317)$	Most likely the $0^+(c\bar{s})$
$D_{sJ}(2460)$	Most likely the $1^+(c\bar{s})$
$D_{sJ}(2632)$	Needs confirmation
$X(3872)$	Molecule? see Voloshin
$X(3943)$	$\eta_c''(3^1S_0)$ - look for $\gamma\gamma \to DD^*$
$Y(3943)$	χ_{c1}' - look for $D\bar{D}$ and DD^*
$Z(3930)$	χ_{c2}' - confirm by DD^*
$Y(4260)$	Hybrid?

To conclude I want to thank experimentalists for all the wonderful results they're providing!

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