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

Stephen Godfrey
Ottawa Carleton Institute of Physics, Department of Physics, Carleton University, Ottawa K1S 5B6, Canada

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 $X(3940)$ is the $Y(2S)$ which can be tested by looking for it in $\gamma\gamma \to D\bar{D}^*$, the $Y(3940)$ is the $\chi_{cJ}(2P_J)$ which can be tested by looking for it in $DD$ and $D\bar{D}$, the $Z(3930)$ is the $\chi_{cJ}(2P_J)$ which can be confirmed by looking for it in $DD^*$. 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 $2^{--}$ it is likely the $1^{++}$ 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 at 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 charmonium state to be observed in almost twenty years. Since then eight new charmonium like states have been observed [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14] plus the $B_c^+$, [15, 16, 17], the puzzling $D_s^{(*)}$ states [18, 19, 20, 21] and the broad $D$ $P$-wave states [22, 23, 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].

An extensive review of quarkonium physics, including other calculations and detailed references, is given in Ref. [27].

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 $S_q$, $\tilde{S}_q$ contact interaction arising from the one-gluon-exchange while the splitting of the $P$-wave $\chi_c$ 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 [28]. For the strong decays we rely on the $2P_0$ decay model which describes most strong decays reasonably well [29, 30, 31, 32, 33, 34, 35]. Decays of charmonium states up to $\sim 4.6$ GeV were calculated by Barnes Godfrey and Swanson [30] with similar results obtained by Eichten Lane and Quigg [37].

FPCP06 221
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 charmonium states
other hadron states are expected. Multiquark states
have a larger quark content than the conventional $q\bar q$
complex and are referred to as “charmonium hybrids” while the other extremes consists of loosely
bound mesons such as $DD$ and are referred to as
molecules. I refer you to Voloshin’s contribution.

The other type of exotic charmonium state are the
so-called hybrid mesons which have an excited gluonic
degree of freedom. These are described by many dif-
ferent models and calculational schemes. 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 charmonium spectrum while the excited
adiabatic surfaces are found by putting the quarks
into more complicated colour configurations. The adi-
abatic potentials have been calculated using Lattice
QCD. In the flux tube model the lowest excited
adiabatic surface corresponds to transverse excita-
tions of the flux tube and leads to a doubly degen-
erate 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 calcu-
lated using many different models. There are some
general properties that seem to be supported by most
models and by recent lattice QCD calculations. Nev-
ertheless 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 $\psi_g$ 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 $DD$ 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 $b\bar b \to c\bar c S$ where $S$
is a light scalar meson.

### 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 spec-
trscopy.

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

**$B_c$** While observed previously, the CDF collabora-
tion recently presented a precise mass measure-
ment which could confront theoretical pre-
dictions. The observed mass of $M(B_c) = 6287.0 \pm 4.8(\text{stat}) \pm 1.1(syst)$ MeV
compares favourably to the lattice QCD result of $6304 \pm 12$ MeV
and the quark potential model result of $6271$ MeV.

**$\eta_c'$** This state was recently observed by Belle and
CLEO. The combined mass of $M(\eta_c') = 3637.4 \pm 4.4$ MeV is slightly higher than the
quark model prediction of $3623$ MeV
so that the quark model slightly overestimates the
$2^3S_1 - 2^3S_0$ splitting. Eichten Lane and Quigg 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 collab-
oration. Its mass of $M(h_c) = 3524.4 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})$ MeV
and the $3^3P_2 - 1^3P_1$ splitting of $M(3^3P_2) - M(1^3P_1) = 1.0 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})$ 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.

Taken together these results provide an important test
of quarkonium spectroscopy calculations and help cal-
ibrate the reliability of the predictions.
4. The $D_{sJ}(2317)$ and $D_{sJ}(2460)$

The $D_{sJ}(2317)$ was first observed by Babar and the $D_{sJ}(2460)$ by CLEO. Both were subsequently seen and studied by Belle. 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 $D^{*}K$ $[18]$. 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 $[19]$. 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 $[19, 50, 51, 52]$. The phenomenology of these states has been discussed elsewhere $[19, 50, 51, 52]$ so I will restrict myself to comments on some new measurements by Babar relating to radiative transitions $[18]$. 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. Babar obtained the following results $[18]$: $B(D_{sJ}(2460)^{-} \rightarrow D_{s}^{-}\gamma) = 0.51 \pm 0.11 \pm 0.09$ $B(D_{sJ}(2460)^{-} \rightarrow D_{s}^{0}\gamma) = 0.15 \pm 0.03 \pm 0.02$ $B(D_{sJ}(2460)^{+} \rightarrow D_{s}^{+}\pi^{+}\pi^{-}) = 0.04 \pm 0.01$ (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 $1P_{1}$ $[51]$: $D_{s1}^{1/2} = -1P_{1}\sin\theta + 3P_{1}\cos\theta$ (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 $3P_{1} - 1P_{1}$ mixing angle via $[54, 55]$: $\Gamma(3P_{1} \rightarrow S_{1} + \gamma) \Gamma(1P_{1} \rightarrow S_{0} + \gamma) = \frac{\omega_{1}^{2}(3P_{1})^{2}}{\omega_{1}^{2}(1P_{1})^{2}}\frac{|3S_{1}|^{2}}{|1S_{0}|^{2}}\sin^{2}\theta \cos^{2}\theta$ (2) where $\omega_{i}$ and $\omega_{s}$ are the photon energies for the two transitions and $|3S_{1}|^{2}$ and $|1S_{0}|^{2}$ 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 $[45, 54]$. 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 $D_{sJ}^{1/2}$ to $D_{s}\gamma$ and $D_{s}^{*}\gamma$ is a means of measuring the $3P_{1} - 1P_{1}$ mixing angle $[54]$.

5. $D_{sJ}(2632)$

This state was observed by the SELEX collaboration in hadroproduction in $D_{s}^{+}\eta$ and $D^{0}K^{+}$ final states $[15]$. 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 $\Gamma(D^{0}K^{+})/\Gamma(D_{s}^{+}\eta) = 0.16 \pm 0.06$. It has not been seen by other high statistics experiments $[54]$ 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 $[54, 52, 60]$. 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 $\Gamma(D^{*}K) > \Gamma(DK) >> \Gamma(D_{s}\eta)$ (3) The total width is predicted to be $\Gamma(D_{sJ}(2632)) = 36$ MeV and $\Gamma(DK)/\Gamma(D_{s}\eta) \approx 9$. 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

FPCP06 221
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 $J/\psi$ in $e^+e^-$ collisions. 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 $BR(X \to D\bar{D}^*) = 96.4_{-3.2}^{+4.5} \pm 22\%$. $BR(X \to D\bar{D}) < 41\%$ (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 $\eta_c$ and $\eta'_c$ are also produced in double charm production. This was also discussed by Eichten Lane and Quigg. The predicted width for a $3^1S_0$ with a mass of 3943 MeV is $\sim 50$ MeV which is not 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 28 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 $2^3P_1(c\bar{c}) \chi'_1(1)$ state. It is natural to try the $2^3P_1(c\bar{c})$ since the $2^1P_1$ states are predicted to lie in the 3920-3980 MeV mass region and the widths are predicted to be in the range $\Gamma(2^3P_1) = 30 - 165$ MeV. 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). 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 $3^1S_0(c\bar{c}) \eta''_c$ 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 $B \to K\pi\pi\pi J/\psi$. 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 $BR(B \to K\chi') \cdot BR(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$. One expects that $BR(B \to K\chi'_{cJ}) < BR(B \to K\chi_c) = 4 \times 10^{-4}$. This implies that $B(Y \to \omega J/\psi) > 12\%$ 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 charmonium 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 $\chi'_c(2^3P_1(c\bar{c}))$ state we expect $DD^*$ to be the dominant decay mode with a predicted width of 135 MeV which is consistent with that of the $Y(3940)$ within the theoretical and experimental uncertainties. Furthermore, the $\chi'_c$ is also seen in $B$-decays.

The decay $1^{++} \to \omega J/\psi$ is unusual. However, the corresponding decay $\chi'_1 \to \omega Y(1S)$ has also been seen. One possible explanation for this unusual decay mode is that rescattering through $DD^*$ is responsible; $1^{++} \to DD^* \to \omega J/\psi$. 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 $\chi'_c(2^3P_1(c\bar{c}))$ state. This can be tested by searching for the $DD$ and $DD^*$ final states and by studying their the angular distributions ($\chi'_c$ can only decay to $DD^*$).

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. The two photon width is measured to be $\Gamma(\gamma\gamma \cdot B_{D\bar{D}} = 0.18 \pm 0.05 \pm 0.03$ 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 $\chi''_c(2^3P_2(c\bar{c}))$ state. (The $\chi''_c$ cannot decay to $D\bar{D}$.) The predicted mass of the $\chi''_c$ is 3972 MeV. The predicted partial widths and total width assuming $M(2^3P_2(c\bar{c})) = 3930$ MeV are $\Gamma(\chi''_c \to D\bar{D}) = 21.5$ MeV, $\Gamma(\chi''_c \to DD^*) = 7.1$ MeV and $\Gamma_{total}(\chi''_c) = 28.6$ MeV in good agreement with the experimental measurements. Furthermore using $\Gamma(\chi''_c \to \gamma\gamma) = 0.67$ keV times $B(\chi''_c \to D\bar{D}) = 70\%$ implies $\Gamma_{\gamma\gamma} \cdot B_{D\bar{D}} = 0.47$ 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 $\chi''_c$. However, for the sake of argument, let us consider the alternative possibility that it is the $\chi''_0$ (which is not supported by the angular distributions). The $\chi''_0$ only decays to $D\bar{D}$ while the $\chi''_c$ decays to both $D\bar{D}$ and $DD^*$. The ratio of $DD^*/D\bar{D}$ is $1/3$. Thus, the $\chi''_0$ interpretation could be confirmed by observation of the $DD^*$ final state. Finally we note that both the $\chi''_c$ and $\chi''_0$ undergo radiative transitions to $\psi'$ with partial widths $\Gamma(\chi''_c \to \gamma\psi') \simeq 200$ keV and $\Gamma(\chi''_0 \to \gamma\psi') \simeq 130$ keV. Eichten Lane and...
Quigg find these decays are suppressed due to coupled channel effects \[37\].

6.4. Production of $\chi_{cJ}^\prime$ via Radiative Transitions

It is potentially possible to observe all three $2^3P_J(cc)$ states in radiative decays of the $\psi(4040)$ and $\psi(4160)$ to $\gamma DD$ and $\gamma DD^* \ [38\]$. The partial widths of $\psi(3S) \rightarrow 2^3P_J \gamma$ 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 $\psi(4040) \rightarrow \chi_{cJ}^\prime \gamma$ 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 $2P(cc)$ 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; $D^0 \overline{D}^0$ molecule, charmonium hybrid, glueball, and a conventional $2^3P_1$ or $1^3D_2$ state.

I'll briefly examine the possible charmonium interpretations \[39, 40, 41, 42\]. 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 $1^3D_2$, $2^3P_0$, $2^1P_1$, and $2^3P_2$ have $C = +$. The observation of $X(3872) \rightarrow \gamma J/\psi$ by Belle \[43\] and Babar \[44\] implies $C = +$. An angular distribution analysis by the Belle collaboration favours $J^{PC} = 1^{++}$ \[45\] although a higher statistics analysis by CDF cannot distinguish between $J^{PC} = 1^{++} \ or \ 2^{++}$ \[46\]. 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 $2^3P_2$ implies a $2P$ mass of $\sim 3940$ MeV which is inconsistent with the $2^3P_1$ interpretation. This leads to the conclusion that the $X(3872)$ is a $D^0 \overline{D}^0$ molecule or “tetraquark” state. This is discussed in detail by Voloshin \[47\]. However, as just mentioned, the $2^{++}$ is not totally ruled out and the predicted $2^3D_2$ 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 $X(3872)$ \[48\].

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^- \rightarrow \gamma_{ISR} J/\psi \pi\pi \ [49\]$. 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 $BR(Y \rightarrow J/\psi \pi^+\pi^-) = 5.5 \pm 1.0 \pm 0.8$ eV. Further evidence was seen by Babar in $B \rightarrow K(\pi^+\pi^- J/\psi) \ [50\]$ and by CLEO in $\sigma(e^+e^- \rightarrow \pi\pi J/\psi)$ \[51\].

The first unaccounted for $1^{--}(cc)$ state is the $\psi(3^3D_1)$. Quark models estimate its mass to be $M(3^3D_1) \approx 4500$ 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 $cc$ state. A number of explanations have appeared in the literature: $\psi(4S) \ [71\]$, tetraquark \[72\], and $c\bar{c}$ hybrid \[73, 74, 75\].

Let us consider the possibility that the $Y(4260)$ is a charmonium hybrid. The flux tube model predicts that the lowest $cc$ hybrid mass is $\sim 4200$ MeV \[53\] 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 $Y \rightarrow J/\psi \pi^+\pi^-$; the branching ratio of $B(Y \rightarrow J/\psi \pi^+\pi^-) > 8.8\%$ combined with the observed width implies that $\Gamma(Y \rightarrow J/\psi \pi^+\pi^-) > 7.7 \pm 2.1$ MeV. This is much larger than the typical charmonium transitions of, for example, $\Gamma(\psi(3770) \rightarrow J/\psi \pi^+\pi^-) \sim 80$ 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 $D_J(2420)$ has a width of $\sim 300$ 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:

| 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 |
| \(X(3943)\) | \(\eta_{c}(c\bar{s})\) - look for \(\gamma\gamma \to DD^{*}\) |
| \(Y(3943)\) | \(\chi_{c1}\) - look for \(D\bar{D}\) and \(DD^{*}\) |
| \(Z(3930)\) | \(\chi_{c2}\) - confirm by \(DD^{*}\) |
| \(Y(4260)\) | Hybrid? |

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

Acknowledgments

The author thanks the organizers of FPCP’06 for their kind invitation and for running a wonderful meeting. He thanks T. Barnes, R. Faccini, C. Hearty, J. Rosner, and E. Swanson for helpful communications and discussions. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.

References

[1] T. Skwarnicki [CLEO Collaboration], Prepared for 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 Jul 2002; G. Bonvicini et al. [CLEO Collaboration], Phys. Rev. D 70, 032001 (2004) arXiv:hep-ex/0404021.
[2] S. K. Choi et al. [BELLE collaboration], Phys. Rev. Lett. 89, 102001 (2002) [Erratum-ibid. 89, 129901 (2002)] arXiv:hep-ex/0206002; K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 89, 142001 (2002) arXiv:hep-ex/0205104.
[3] D. M. Asner et al. [Cleo Collaboration], Phys. Rev. Lett. 92, 142001 (2004) arXiv:hep-ex/0312058.
[4] J. L. Rosner et al. [CLEO Collaboration], Phys. Rev. Lett. 95, 102003 (2005) arXiv:hep-ex/0505073.
[5] K. Abe et al., arXiv:hep-ex/0507019.
[6] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 94, 182002 (2005) arXiv:hep-ex/0408120.
[7] S. Uehara et al. [Belle Collaboration], Phys. Rev. Lett. 96, 082003 (2006) arXiv:hep-ex/0511203.
[8] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 95, 142001 (2005) arXiv:hep-ex/0506081.
[9] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 73, 011101 (2006) arXiv:hep-ex/0504090.
[10] T. E. Coan et al. [CLEO Collaboration], Phys. Rev. Lett. 96, 162003 (2006) arXiv:hep-ex/0602034.
[11] S. K. Choi et al. [Belle Collaboration], Phys. Rev. Lett. 91, 262001 (2003) arXiv:hep-ex/0309032.
[12] D. Acosta et al. [CDF II Collaboration], Phys. Rev. Lett. 93, 072001 (2004) arXiv:hep-ex/0312021.
[13] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 93, 162002 (2004) arXiv:hep-ex/0405004.
[14] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 71, 071103 (2005) arXiv:hep-ex/0406022.
[15] F. Abe et al. [CDF Collaboration], Phys. Rev. Lett. 81, 2432 (1998) arXiv:hep-ex/9805034.
[16] F. Abe et al. [CDF Collaboration], Phys. Rev. D 58, 112004 (1998) arXiv:hep-ex/9801102.
[17] D. Acosta et al. [CDF Collaboration], Phys. Rev. Lett. 96, 082002 (2006) arXiv:hep-ex/0505070.
[18] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 90, 242001 (2003).
[19] D. Besson et al. [CLEO Collaboration], Phys. Rev. D 68, 032002 (2003).
[20] K. Abe et al., Phys. Rev. Lett. 92, 012002 (2004) arXiv:hep-ex/0307052.
[21] A. V. Evdokimov et al. [SELEX Collaboration], Phys. Rev. Lett. 93, 242001 (2004) arXiv:hep-ex/0406045.
[22] K. Abe et al. [Belle Collaboration], Phys. Rev. D 69, 112002 (2004).
[23] J. M. Link et al. [FOCUS Collaboration], Phys.
See, for example, T. Barnes, F. E. Close and S. Anderson et al.

S. Godfrey and N. Isgur, Phys. Rev. D 32 (1985) 189.

N. Brambilla et al., arXiv:hep-ph/0412158

See, for example W. Kwong and J. L. Rosner, Phys. Rev. D 38, 279 (1988).

L. Micu, Nucl. Phys. B10, 521 (1969).

S. Godfrey and N. Isgur, Phys. Rev. D 28, 2791 (1983). [arXiv:hep-lat/0205255]

M. B. Voloshin, arXiv:hep-ph/0605063

For a recent review see P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003).

B. Aubert [BABAR Collaboration], arXiv:hep-ex/0604030

S. Godfrey, Phys. Rev. D 72, 054029 (2005) [arXiv:hep-ph/0508078].

S. Godfrey, Int. J. Mod. Phys. A 20, 3771 (2005) [arXiv:hep-ph/0409236].

B. Aubert et al. [BABAR Collaboration], arXiv:hep-ex/0408087.

S. Godfrey and R. Kokoski, Phys. Rev. D 43, 1679 (1991).

For a recent review see P. Colangelo, F. De Fazio and R. Ferrandes, Mod. Phys. Lett. A 19, 2083 (2004) [hep-ph/0407137].

W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003).

S. Godfrey, Phys. Lett. B 568, 254 (2003).

B. Nicolescu and J. P. B. de Melo, arXiv:hep-ph/0407088.

T. Barnes, private communication.

Flavor Physics and CP Violation Conference, Vancouver, 2006