The XYZs of $c\bar{c}$

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Abstract. In this invited contribution I summarize the status of the new charmonium-like
states near and above 3.9 GeV, which are the X(3872), X(3943), Y(3943), Z(3931), Y(4260)
and $\psi(4320)$. First I review the spectrum of conventional charmonium states in the context of
a potential model, following which I discuss the status of these new states and consider whether
they might be charmonia or charmonium hybrids, and how these possibilities might be tested
in future.

1. Introduction
Recent years have seen remarkable progress in our knowledge of the spectrum of charmonium
states, due to the many contributions from B factories (as was anticipated theoretically by
Eichten et al. [1]), as well as the more traditional approaches such as $e^+e^-$ machines (CLEO-c
and BES) and hadronic facilities (Fermilab). In this invited contribution I will summarize our
knowledge of the new states near and above 3.9 GeV, and suggest ways in which the nature of
these states can be investigated in future. First however I will begin with a brief reminder of
our understanding of the conventional charmonium spectrum.

2. The Spectrum of Conventional Charmonium
The known spectrum of charmonium candidates has until recently been in remarkably good
agreement with potential model predictions; Fig.1 for example shows the charmonium spectrum
in a potential model (abstracted from Ref.[5] and updated) compared to experiment. The
assumptions in this model are a Coulomb plus linear static potential, with the spin-dependent
$O(v^2/c^2)$ forces predicted by one gluon exchange and Lorentz scalar confinement. The four
parameters in this model were fitted to the known states below the open-charm (DD) threshold
of 3.73 GeV, and the remaining levels (dashed) are predictions of the model. Evidently the
simple physics incorporated in this model explains much of the charmonium spectrum below
3.73 GeV. We note in passing that there are more fundamental studies of charmonium using
lattice QCD, which thus far have found results for the spectrum of states that are quite similar
to the predictions of potential models.

Although the charmonium system is in good agreement with naive potential model
predictions, the spectrum of charm-strange mesons is not. The surprises in this sector [2, 3, 4]
and the discovery of the very narrow X(3872) motivated several recent detailed theoretical studies
of charmonium spectroscopy [5, 6]. Studies of the strong decays of states above the open-charm
threshold of 3.73 GeV [5, 6] showed that in addition to the narrow $2^{-+}$ and $2^{--}$ states, the
$3^{--} 3D_3$ $c\bar{c}$ state should also be quite narrow ($< 1$ MeV) due to the large F-wave centrifugal
barrier against its decay mode DD. All of the allowed open-charm strong decay amplitudes and E1 electromagnetic partial widths of the $c\bar{c}$ states up to 4.42 GeV were evaluated in these theoretical studies, and future comparisons of these predictions with experimental results will provide interesting tests of our understanding of the physics of charmonium.

**Figure 1.** The current experimental status of charmonium (and possible charmonium hybrid) spectroscopy, compared to the predictions of a nonrelativistic potential model. Experimental levels are solid lines, and theoretical levels are dashed. The open-charm threshold at 3.73 GeV is also shown.

### 3. The XYZ states

#### 3.1. X(3872)

The first of the surprising new discoveries in the charmonium sector was the X(3872), which was found by the Belle Collaboration at KEK [7], in the final state $J/\psi \pi^+ \pi^-$. Although it was initially thought that this might be one of the as yet undiscovered narrow D-wave $2^-$ states, the mass and width were found to be inconsistent with this assignment [8].

The near degeneracy of the X with the mass of a neutral $D^0\bar{D}^*$ pair suggested that this might instead be an S-wave DD$^*$ molecule, strongly isospin violating since it would be largely a neutral pair [9, 10]. One would expect a weakly bound DD$^*$ system if bound by pion exchange [11] to have $J^{PC} = 1^{++}$ quantum numbers, and there is now much evidence that this $J^{PC}$ assignment is correct [12]. The recent observation of the X(3872) with comparable strength in the two modes $J/\psi \rho^0$ and $J/\psi \omega$ [13] is the most striking evidence of the validity of this $D^0\bar{D}^*$ charm molecule model. Thus the early speculations [14, 15] that there might be charmed meson molecules appear to be confirmed, although not the $\psi(4040)$ as was originally suggested.

#### 3.2. The XYZ States Near 3.9 GeV

Three of the states discovered in recent experimental studies, the X(3943), Y(3943) and Z(3931), have masses roughly consistent with expectations for 2P states (radial excitations of the $\{\chi_J\}$)
and perhaps the $3S\eta'$; see Fig.1. These obvious $c\bar{c}$ assignments should be explored in detail before more exotic interpretations such as molecules or anomalously light $c\bar{c}$ hybrids are seriously entertained.

### Table 1. Allowed open-charm decay modes and partial widths ($^3P_0$ model) of $C= (+) 2P$ $c\bar{c}$ states.

| State       | Quantum Numbers | Mode     | Width (MeV) |
|-------------|-----------------|----------|-------------|
| $\chi_2'(3929)$ | $2^3P_2 (2^{++})$ | DD$^*$   | 11.3        |
|             |                  | DD       | 34.3        |
| $\chi_1'(3940)$ | $2^3P_1 (1^{++})$ | DD$^*$   | 140.        |
| $\chi_0'(3940)$ | $2^3P_0 (0^{++})$ | DD       | see text    |

Since the only open-charm strong decay modes available to these states are DD and DD$^*$, a simple comparison of the states observed in these two decay modes can provide valuable information. The predicted partial widths of $2P$ states into these modes in the $^3P_0$ decay model of Ref.[5], generalized to the masses indicated, are given in Table 1. Note that the width of the $\chi_0'$ is problematic, as there is a node in the $^3P_0$ model DD decay amplitude near the physical point.

#### 3.2.1. Z(3931)  
Of the three new XYZ states, the Z(3931) and its proposed assignment should be the easiest to test in future experiments. This state was reported by the Belle Collaboration [16] in $\gamma\gamma$ collisions, in the processes $\gamma\gamma \rightarrow Z(3930) \rightarrow D^+D^-$ and $D^0\bar{D}^0$. Belle suggested that this might be the radially excited $J=2$ $\chi_2'$, since there is a preference for $J=2$ in the DD angular distribution.

The reported strength of the combined $\gamma\gamma$ and DD couplings is indeed roughly consistent with this $\chi_2'$ assignment. The published [16] Belle results are

\[
M = 3929 \pm 5 \pm 2 \text{ MeV},
\]

\[
\Gamma = 29 \pm 10 \pm 2 \text{ MeV}
\]

and

\[
\Gamma_{\gamma\gamma} \cdot B_{DD} \bigg|_{\text{exp.}} = 0.18 \pm 0.05 \pm 0.03 \text{ keV}.
\]

In comparison, the quark model predicts a two-photon width for a $\chi_2'$ of about $\Gamma_{\gamma\gamma} = 0.64 \text{ keV}$ [17]. (Münz [18] quotes theoretical results for this number from several models, which give $\Gamma_{\gamma\gamma} = 0.317 - 0.684 \text{ keV}.$) This should be multiplied by the DD branching fraction, which is about 75% in the $^3P_0$ decay model of Ref.[5], when generalized to a $\chi_2'$ mass of 3.929 GeV. Combining the $\Gamma_{\gamma\gamma}$ range quoted by Münz and the predicted DD branching fraction gives the theoretical result

\[
\Gamma_{\gamma\gamma} \cdot B_{DD} \bigg|_{\text{theor.}} = 0.24 - 0.51 \text{ keV}.
\]

Given the uncertainties in these calculations, this may be regarded as rough agreement between theory and experiment for a $\chi_2'$. The definitive test of this assignment would be the observation of a DD$^*$ mode; the expected relative branching fraction is $\text{DD}^*/\text{DD} = 0.35$, and the only plausible competing assignment, $0^{++} \, ^3P_0$, does not lead to a DD$^*$ final state. (The $1^{++} \, ^3P_1$ of course cannot be made in $\gamma\gamma$ collisions.)
3.2.2. X(3943) The X(3943) was reported by Belle [19] in the double charmonium production reaction $e^+e^- \rightarrow J/\psi$ X(3943) in the final state DD*, in both charged and neutral modes. The fitted mass and width are

\[
M = 3943 \pm 6 \pm 6 \text{ MeV};
\]

\[
\Gamma = 15 \pm 10 \text{ MeV or } < 52 \text{ MeV (90\% c.l.)}.
\]

Since the only other charmonium states seen recoiling against the $J/\psi$ with comparable strength in this (poorly understood) process are the $\eta_c$, $\chi(0)$ and $\eta_c''$, the obvious assignment for this state is $\eta_c''$. ($\chi(0)$ cannot decay to DD*).

The reported total width however is surprisingly small for an $\eta_c''$ assignment; one expects $\Gamma = 70$ MeV in the $^3P_0$ decay model, using the reported mass as input. Of course the experimental total width is not very well determined, and the discrepancy may disappear with better statistics. The mass is also surprising for an $\eta_c''$, since it is about 100 MeV below the presumably $^3S_1$ partner $\psi(4040)$; in the 2S states, the $\psi' - \eta_c'$ splitting in contrast is only about 30 MeV. If the X(3943) is indeed the $\eta_c''$, the mass is not yet accurately determined, or there are important mass shifts in the 3S states relative to 2S. Testing the $\eta_c''$ assignment is a simple matter of establishing whether the angular distribution of DD* final states is P-wave ($J^P = 0^-$); alternative J=1 and J=2 2P assignments lead to S- and D-wave DD* final states.

3.2.3. Y(3943) This may be the least well established of the new XYZ states. Evidence for this state was reported by Belle [20] as an $\omega J/\psi$ threshold enhancement in the charged B decays $B^\pm \rightarrow K^\mp \omega J/\psi$. Assuming that this was due to a resonance, Belle quoted a mass and width of

\[
M = 3943 \pm 11 \pm 13 \text{ MeV},
\]

\[
\Gamma = 87 \pm 22 \text{ MeV}.
\]

Of course the observation of a charmonium state in a closed-charm final state such as $\omega J/\psi$ with a relatively large branching fraction ($B_{B^+ \rightarrow K^+ \omega J/\psi} \cdot B_{Y \rightarrow \omega J/\psi} = 7.1 \pm 1.3 \pm 3.1 \cdot 10^{-5}$) is very surprising, since the corresponding close-charm decay partial width for $\psi' \rightarrow J/\psi \pi \pi$ is only about 140 keV. Since the Y(3943) has a total width near 100 MeV, one might expect an $\omega J/\psi$ branching fraction of roughly $10^{-3}$. Since the known total B meson branching fractions to the 1P $c\bar{c}$ states such as the $\chi_c$ are only an order of magnitude larger, for example $B_{B^+ \rightarrow K^+ \chi_c} = 5.3 \pm 0.7 \cdot 10^{-4}$, the reported Y(3943) signal appears to imply an anomalously large branching fraction for Y(3943) → $\omega J/\psi$. Either the Y(3943) is quite unusual in populating this decay mode, or it is not actually due to a resonance.

The mass, width and $\omega J/\psi$ decay mode of this state, and the fact that the $2^{++}$ 2P state is likely the Z(3931), suggest that the least implausible $c\bar{c}$ assignment for the Y(3943) is $1^{++}$ $2^3P_1$. This state is predicted to have a total width of about 140 MeV, dominantly into the open-charm mode DD*. A search for this signal in DD*, with a much larger branching fraction than $\omega J/\psi$, is the obvious test of this assignment. If this assignment is correct, the closed-charm mode $\omega J/\psi$ may have come about through an inelastic final state interaction, Y(3943) → (DD*, $D^*D^*$) → $\omega J/\psi$. The fact that these are near-threshold S-wave processes would enhance this FSI effect.

3.3. Accessing the 3.9 GeV XYZ States

We note in passing that the $\psi(4040)$ and $\psi(4160)$ can be used as $1^{--}$ entry states for the study of the new XYZ states near 3.9 GeV. As shown in Table 2, both these states are expected to have relatively large E1 branching fractions into the 2P $c\bar{c}$ multiplet, $\psi(4040,4160) \rightarrow \gamma\chi_c'$. 


Table 2. Theoretical E1 radiative partial widths of the $\psi(4040)$ and $\psi(4160)$ into $C = (+) \ 2P \ c\bar{c}$ states.

| Initial State | Final State | E1 Width (keV) | E1 B.F. |
|---------------|-------------|----------------|---------|
| $\psi(4040)$  | $\chi'_2(3929)$ | 56.0          | $0.7 \cdot 10^{-3}$ |
|               | $\chi'_1(3940)$ | 25.0          | $0.3 \cdot 10^{-3}$ |
|               | $\chi'_0(3940)$ | 8.3           | $0.1 \cdot 10^{-3}$ |
| $\psi(4160)$  | $\chi'_2(3929)$ | 9.9           | $0.1 \cdot 10^{-3}$ |
|               | $\chi'_1(3940)$ | 129.0         | $1.3 \cdot 10^{-3}$ |
|               | $\chi'_0(3940)$ | 172.1         | $1.7 \cdot 10^{-3}$ |

(These E1 partial widths were calculated as in Ref.[5], for the masses given in the table.) This may allow the identification of the 2P resonances through their subsequent hadronic decays. In this approach one would study the invariant mass and angular distributions of the final charmed mesons in the processes $e^+e^- \to \psi(4040, 4160) \to \gamma DD$ and $\gamma DD^*$. 

3.4. The new states above 4.2 GeV: $Y(4260)$ and $\psi(4320)$

The recently discovered $1^{--}$ states $Y(4260)$ [21, 22] and 4350 MeV [23] appear unlikely as $c\bar{c}$ candidates, since the previously known $1^{--}$ states $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ fill the available $1^{--} \ c\bar{c}$ assignments to just above 4.4 GeV. The new states have been reported only in the closed-charm modes $J/\psi \pi \pi$ and $\psi' \pi \pi$ respectively, which are naively expected to be very weak. (Of course there is an LGT prediction that heavy-flavor hybrids might preferentially populate similar closed-flavor modes [24].) Here the most important task is probably to search for these states in all accessible open-charm modes, which might be expected to be dominant even in hybrids.

3.5. An application for the $\psi(4415)$

Finally, the highest-mass $c\bar{c}$ state currently known is the $1^{--} \ \psi(4415)$, which is usually given a $4^3S_1$ assignment. Although it is not an XYZ state, it could easily be accessed at an $e^+e^-$ facility that is investigating the $Y(4260)$ and $\psi(4320)$, so it may be appropriate to make some observations about what could be learned from studies of this state as well. Nothing is currently known about the exclusive decay modes of the $\psi(4415)$. (The PDG [25] says that the $\psi(4415)$ decays dominantly to “hadrons”, which is not especially surprising.) Calculations of the decay branching fractions of a $4^3S_1 \ c\bar{c} \ \psi(4415)$ in the $^3P_0$ model [5] predict that the largest mode should be the unusual DD$^*$, and in pure D-wave rather than S-wave! It would clearly be a very interesting test of strong decay models to measure the strong decay amplitudes and branching fractions of this state. There is also an “industrial” application of the $\psi(4415)$; by running on the high mass tail of this resonance, one can expect a relatively large branching fraction into the enigmatic $D_{s0}(2317)$ [5, 26], which otherwise is very difficult to produce with useful statistics. A study of interesting decays such as the radiative branching fraction of the $D_{s0}(2317)$ into $\gamma D^*_s$ could then be carried out, for example at BES; this would be valuable in determining the relative size of the $cs$ and $DK$ components of the $D_{s0}(2317)$. 

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