Charmonium tetraquarks or a new light quark?

Scott Chapman\textsuperscript{1,*}

\textsuperscript{1}Institute for Quantum Studies, Chapman University, Orange, CA 92866, USA

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The existence of a fourth flavor of down-type quark with a mass of approximately 1.6 GeV is hypothesized. The right-handed component of this quark is assumed to decay to a right-handed charm quark and a virtual W boson. Many of the recently discovered exotic charged charmonium-like resonances are re-interpreted as mesons involving the new quark.

This paper assumes the following hypothesis: There is a fourth down-type quark with a mass of approximately 1.6 GeV that decays to a right-handed charm quark and a virtual W boson. Based on this hypothesis, many of the exotic “charmonium-like” resonances are mapped to normal $q\bar{q}$ mesons involving this new quark. Before performing the mapping, it is worth reviewing other motivations for such a new light quark.

In a recent paper, it was shown that fits to CKM data could be improved if there was a fourth-generation down-type quark whose right-handed component connected via the W boson with the right-handed charm quark [1]. Such a quark would also help explain the persistent (albeit low-\sigma) excess in charm seen in high-energy collisions. A quark like this would have been produced in pairs in the $e^+e^- \rightarrow Z/\gamma^* \rightarrow q\bar{q}$ experiments at LEP, presumably causing a conflict with the fact that the experimental hadron cross sections agree to high precision with Standard-Model predictions [2]. However, the two W boson connections of the charm quark (left-handed to strange, right-handed to the new quark) also imply a different Z boson coupling for the charm quark. This different coupling combined with new-quark pair production generates experimental results very similar to those predicted by the Standard Model. In addition, direct searches do not rule out such a quark. In other words, existence of the new quark would not conflict with measured data [1].

The recently discovered charged charmonium-like resonances (and some of the neutral resonances) are mostly interpreted in the literature as tetraquarks or other structures such as hadrocharmonium or meson molecules. As mentioned above, this paper re-interprets many of those resonances as normal mesons involving the new, fourth down-type quark. This new quark will be designated by an $f$ in the discussion below, while the other quarks are designated by their first letter.

If such a quark exists, it should be produced in quark-antiquark pairs in $e^+e^-$ collisions. Resonances should be seen for $f\bar{f}$ mesons that have the quantum numbers $J^{PC} = 1^{--}$. With that in mind, the following Quark Model (QM) mapping is proposed for the exotic charmonium-like resonances $Y(4260)$, $Y(4360)$ and $Y(4660)$ [3, 4]:

| Name       | Mass   | Decay         | QM     |
|------------|--------|---------------|--------|
| $Y(4260)$  | 4220   | $\pi^\pm Z_c(3900)^\mp$ | $2^1S_1$ | 534     |
| $Y(4360)$  | 4347   | $\pi^\pm Z_c(4055)^\mp$ | $1^3D_1$ | 573     |
| $Y(4660)$  | 4652   | $\pi^\pm \bar{\psi}(2S)$ | $3^3S_1$ | 612     |

All masses and widths above are in MeV. The QM column shows the proposed quark model mapping of the above resonances as $f\bar{f}$ $1^{--}$ mesons. The $\Delta m$ column shows the difference in mass between the $f\bar{f}$ meson and the $c\bar{c}$ meson with the same QM mapping. Only one decay mode is presented for each resonance; the first two are presented since they illustrate decays to other exotic $"Z_c"$ resonances. It should be noted that the $Y(4260)$ resonance was renamed $\psi(4230)$ by PDG after it was found to have an asymmetric distribution with a much lower mass than previously thought [3].

According to the hypothesis, the $\bar{f}$ quark decays to a $\bar{c}$ quark and a virtual $W^+$ boson which could then decay to a $\pi^+$ (or to a $K^+$ with Cabibbo suppression). From the above decays of the $Y(4260)$ and $Y(4360)$, one could then interpret the $Z_c(3900)^-$ and $Z_c(4055)^-$ as $f\bar{c}$ mesons. Adding in two more charged charmonium-like resonances reported in the literature, the following mapping is proposed for $f\bar{c}$ mesons [4–7]:

| Name        | $J^P$ | Mass   | Decay       | QM     |
|-------------|-------|--------|-------------|--------|
| $Z_c(3885)$ | 1$^+$ | 3884   | $\pi h_c$  | $1^1P_1$ | 373 |
| $Z_c(3900)$ | 1$^+$ | 3898   | $\pi J/\psi$ | $1^3P_1$ | 373 |
| $Z_c(4020)$ | ?     | 4024   | $\pi h_c$  | $2^1S_0$ | 386 |
| $Z_c(4055)$ | ?     | 4056   | $\pi \psi(2S)$ | $2^3S_1$ | 370 |

where the $Z_c(4055)$ has only been observed with $3\sigma$ significance. The mass difference column (comparing to $c\bar{c}$ mesons with the same QM designations) demonstrates the consistency of the mapping. It is also the reason for the hypothesized mass of 1.6 GeV for the new quark.

According to the hypothesis, the decays of the above $f\bar{c}$ mesons to charmonium mesons can be understood as follows:

$$f\bar{c} \rightarrow c\bar{c} + W^- \rightarrow c\bar{c} + d\bar{u}.$$  \hspace{1cm} (3)
In this model, it would also be possible for the $f\bar{c}$ mesons to decay to a charmonium meson and a kaon, but those decays would be Cabibbo suppressed.

From B meson decay, two additional charged $Z_c$ resonances have been confirmed and measured with over 5σ significance. These are the $Z_c$ (4200) and the $Z_c$ (4430) [8]. Since they decay to $\pi J/\psi$ and $\pi\psi(2S)$, respectively, it is tempting to map them analogously to the $Z_c$ (3900) as $3^3P_1$ and $3^1P_1$ $f\bar{c}$ mesons. The difficulty with mapping these resonances to $f\bar{c}$ (or $f\bar{u}$) mesons is that their production mechanism from B meson decay would require two W boson interactions rather than one. As a result, these resonances are not mapped as new $f\bar{c}$ (or $f\bar{u}$) mesons in this paper.

Additional “$Z_{cs}$” resonances have been observed in $e^+e^- \to K^+Z_{cs}$ processes [9]. In the model presented here, those resonances can be interpreted as $f\bar{u}$ mesons. Production can happen in one of two ways:

\[
e^+e^- \to \bar{c}\bar{c} \to c\bar{s} \to f\bar{s} + u\bar{u} \to f\bar{u} + u\bar{s},
\]

\[
e^+e^- \to f\bar{f} \to f\bar{u} + W^+ \to f\bar{u} + u\bar{s},
\]

where $u\bar{u}$ in the first mechanism is by gluon emission, and the second mechanism is highly CKM-suppressed.

The decay of an $f\bar{u}$ meson proceeds as follows:

\[
f\bar{u} \to c\bar{u} + W^- \to c\bar{u} + s\bar{c}.
\]

This decay would show up as a resonance in $D\bar{D}_s$ production. If the hypothesis is correct, then decays to $D\pi$ should also be prevalent. Decays to $D\bar{D}$ or $DK$ would also be possible, but they would be Cabibbo suppressed. With that in mind, the $Z_{cs}$ (3985), $Z_{cs}$ (4000) and $Z_{cs}$ (4220) are mapped to the $3^3P_1$, $3^1P_1$ and $3^3D_1$ states of $f\bar{u}$. According to the hypothesis, one would also predict the existence of neutral $f\bar{d}$ partners to these resonances.

The first production mechanism shown above for a $Z_{cs}$ resonance includes $c\bar{c} \to f\bar{s} + u\bar{u}$. This brings up the possibility that some neutral $f\bar{s}$ mesons could be produced in $e^+e^- \to \pi^0 + f\bar{s}$ processes. One way that such a meson could decay into mesons involving a charm and anti-charm quark is the following: (i) the $f\bar{s}$ would change into $c\bar{c}$ via exchange of a W, and (ii) virtual photon emission would produce a $\pi^0$. The neutral $Z_c$ (4020) [8] has this decay behavior [7], so it could potentially be interpreted as an $f\bar{s}$ meson resonance.

Finally, it is interesting to consider the $X$ (6900) neutral resonance that was discovered as a peak in $J/\psi$ pair production [10]. Since it is neutral, it could be an $f\bar{d}$, $f\bar{s}$ or an $f\bar{b}$ meson (or one of their conjugates). The narrow width and mass of the $X$ (6900) suggest that it may be an $f\bar{b}$ meson. Exchange of a W boson could change the meson into $c\bar{c}$ while gluon emission could create another $c\bar{c}$ and they could recombine into a pair of $J/\psi$s. The resonance’s mass of 6.9 GeV is 2.56 GeV less than the mass of the $b\bar{b}$ meson with QM designation $1^3S_1$ (the $Y(1S)$). That would be the correct mass difference if the new quark has a mass of 1.6 GeV, so a designation of $f\bar{b}$ with $1^3S_1$ for $X$ (6900) would be consistent with the other mappings of this paper. It will be interesting to see if the $J^{PC}$ for the $X$ (6900) is measured in the future to be $1^{--}$.

In summary, starting with the hypothesis that there is a fourth down-type quark with a mass under 1 TeV (2022), arXiv:2203.03007.

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