Do some exotic charmonium-like hadrons involve a new quark?

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(Dated: August 30, 2022)

The existence of a fourth flavor of down-type quark with a mass of 1.6 GeV is hypothesized. It is assumed that the W boson connects the right-chiral components of this quark and the charm quark. Some of the recently discovered exotic charmonium-like “Y” and “R” hadron resonances are re-interpreted as normal $q\bar{q}$ mesons involving the new quark. Predictions are made for the masses of additional mesons involving the new quark.

This paper assumes the following hypothesis: There is a fourth down-type quark whose mass is $\sim 400$ MeV greater than that of the charm quark. This new quark can decay to a right-handed charm quark and a virtual W boson. Before re-interpreting specific exotic resonances in light of this proposed quark, it is worth reviewing other motivations for the new quark.

In a recent paper, it was shown that fits to CKM data could be improved if there was a fourth down-type quark whose right-chiral component connected via the W boson with the right-chiral charm quark [1]. Such a quark would also help explain the persistent (albeit low-$\sigma$) excess in charm seen in high-energy collisions. Since a quark like this would have been produced in pairs in $e^+e^-\rightarrow Z/\gamma^*\rightarrow q\bar{q}$ experiments at LEP, its presence would presumably conflict with the fact that the experimental cross section and asymmetry data were reproduced to high precision using just the Standard-Model quarks [2]. However, the two W boson connections of the charm quark proposed here (left-chiral to strange, right-chiral to the new quark) also imply different Z boson couplings for the charm quark. These different couplings combined with new-quark pair production generate experimental results very similar to those predicted by the Standard Model [1]. Surprisingly, direct searches do not rule out such a quark. In other words, existence of the hypothesized new quark would not conflict with precision electroweak data or direct searches [1].

The recently discovered “Y” and “R” charmonium-like resonances are mostly interpreted in the literature as tetraquarks or other 4-quark hadrons such as hadrocharmonium or meson molecules. This paper re-interprets some of those resonances as normal $q\bar{q}$ 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, some of the exotic “Y” and “R” hadrons produced in $e^+e^-$ collisions are interpreted as normal $f\bar{f}$ Quark Model (QM) resonances in the following way:

\[
\begin{array}{cccccc}
\text{Name} & \text{Mass} & \Gamma & \text{QM} & \Delta m_c & \Delta m_b \\
R(3760) & 3766 & 22 & 1^3S_1 & 335 & 2847 \\
Y(4230) & 4234 & 17.6 & 2^3S_1 & 274 & 2895 \\
Y(4360) & 4372 & 115 & 1^3D_1 & 299 & 2896 \\
Y(4660) & 4630 & 72 & 3^3S_1 & 295 & 2863 \\
\end{array}
\]

where masses and widths are in MeV. The $Y(4230)$ data are from [3], $R(3760)$ is from [4], and the rest of the masses and widths are from [5]. The QM column above and the figure below show the proposed Quark Model mapping of the above resonances as $f\bar{f} 1^{--}$ mesons.

\[\text{Fig. 1. Proposed } 1^{--} \text{ mesons involving the new quark.}\]

The center panel of Fig. 1 was taken from [6]. The $\Delta m_c$
and $\Delta m_b$ columns of table (1) show half the difference in mass between the $ff$ meson and the $\bar{c}c$ and $\bar{b}b$ mesons with the same QM mapping, respectively.

It is interesting to compare the widths of the $\psi(2S)$ and the $Y(4230)$, since they are hypothesized to have the same quark model designation of $2^1S_1$. The width of the former is $0.294 \pm 0.008$ MeV [5], while that of the latter was most recently measured to be $17.6 \pm 8.1 \pm 0.9$ MeV [3]. The larger mass of the $Y(4230)$ gives it more options for decay than the $\psi(2S)$, so one would expect it to be wider, but possibly not by a factor of 60. It is worth noting that the most recent measurement of the width of the $Y(4230)$ is only $2\sigma$ away from 1 MeV.

The hypothesis of a new quark could help explain the following: From the discovery of the $J/\psi$ until 2002, it was believed that any $1^{--} \bar{c}c$ resonance with a mass above the $DD$ open charm threshold would decay with almost 100% branching ratio to open charm products $D\bar{D}$. But for the last 20 years a number of experiments have established that at energies near the $\psi(3770)$ resonance, a significant percentage of decays ($\sim 16\%$) go to non-open-charm products, including $J/\psi$ [4]. These data and other experimental evidence led to the discovery of the $R(3760)$ shown in table (1). If the $R(3760)$ was an $ff$ meson, it could be a major contributor to the large number of non-open-charm decays.

The following decays have been observed [7], [8]:

\begin{equation}
Y(4230) \rightarrow \pi^+Z_c(3900)^- + c.c. \rightarrow \pi^+\pi^- J/\psi \\
Y(4230) \rightarrow \pi^0Z_c(3900)\bar{0} \rightarrow \pi^0\pi^0 J/\psi, (2)
\end{equation}

where c.c. denotes the charge conjugate. At $\sqrt{s}$ energies of 4.23 and 4.26 GeV, it was determined that 23% and 14% of the observed $Y(4230) \rightarrow \pi^+\pi^- J/\psi$ events went through the $Z_c(3900)^+$ resonance [7]. This high percentage suggests that $Y(4230) \rightarrow \pi^+Z_c(3900)^-$ is most likely not a weak decay mediated by the $W$ boson (e.g., not $ff \rightarrow f\bar{c} + \pi^+$).

So it is assumed in this paper that the $Z_c(3900)$ resonances are the same structures as they are usually assumed to be in the literature: either 4-quark hadrons, or else cusp or threshold effects. But with the hypothesis of this paper, new possibilities arise. Within the context of these models, a new threshold is in place: the $Z_c(3900)$ mass is slightly smaller than the combined masses of $R(3760)$ and a pion. This opens the possibilities of 4-quark structure involving $ff$ or of new cusp or threshold effects.

If the proposed quark exists, it should be seen not only in $ff$ mesons, but also in mesons involving other quarks. Assuming the mass of the new quark is roughly 400 MeV larger than the mass of the charm quark, the following predictions are made:

| Predicted $1^1S_0$ Mesons |
|---------------------------|
| Quarks | Mass | $\Delta m_c$ | $\Delta m_b$ |
| $f\bar{u}, f\bar{d}$ | $\sim 2270$ | 401 | 3009 |
| $f\bar{s}$ | $\sim 2360$ | 392 | 3007 |

According to the hypothesis, the $1^1S_0$ $f\bar{u}$ and $f\bar{d}$ mesons would be expected to decay as follows:

\begin{equation}
f\bar{u} \rightarrow c\bar{u} + W^- \rightarrow D^0\pi^- \\
f\bar{d} \rightarrow c\bar{d} + W^- \rightarrow D^+\pi^-.
\end{equation}

The FOCUS collaboration studied the invariant mass associated with production of $D^0\pi^\pm$ and $D^\mp\pi^\pm$. A good fit to the data was achieved once the known $D$ resonances, $D$ meson feed-downs, and an additional broad resonance were taken into account [9]. That being said, in figs 2c and 2d, 1-2 data points at around 2270 MeV are 1-2$\sigma$ above the fit, both for the charged and neutral resonces. It would be interesting to perform updated measurements of $D\pi$ invariant masses at high resolution in that mass range to see if a narrow resonance could be found.

The proposed mass of the $1^1S_0 f\bar{s}$ state is just below the sum of the masses of a $D$ meson and a kaon. It is also below the sum of masses of the $f\bar{u}$ meson and a pion. Two possible decays for the $f\bar{s}$ are:

\begin{equation}
f\bar{s} \rightarrow c\bar{s} + W^- \rightarrow D^+_s\pi^- \\
f\bar{s} \rightarrow c\bar{s} + W^- \rightarrow s\bar{s} + gg \rightarrow K^+K^-\eta' + c.c.,
\end{equation}

where $g$ represents a gluon, and the second decay involves a $W$ boson in a loop.

The BESIII collaboration has measured the $X(2370)$ resonance with the decay products of the second decay above. In figs 3a and 3b of [10], the wide bump for the $X(2370)$ is clearly visible, but there is also a possible hint of something very narrow at around 2360 MeV. It would be interesting to perform updated measurements at high resolution in that mass range to see if a narrow resonance could be found. It would also be interesting to search for a resonance at 2390 MeV that decays to $D^+_s\pi^- + c.c.$.

As mentioned above, the hypothesis of this paper in no way excludes the possibility of tetraquarks, hadrocharmonium, meson molecules, or pentaquarks. To the contrary, it is assumed that most of the observed exotic resonances are these structures. The hypothesis simply proposes that in addition to these exotic states comprised of the known quarks, there may also be some mesons (and baryons, tetraquarks, etc.) that involve the new quark. It will be interesting to see whether future experimental data support or disprove the hypothesis.

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