Four Quark Interpretation of $Y(4260)$

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We propose that the $Y(4260)$ particle recently announced by BaBar is the first orbital excitation of a diquark-antidiquark state ($[cs][\bar{s}\bar{c}]$). Using parameters recently determined to describe the $X(3872)$ and $X(3940)$ we show that the $Y$ mass is compatible with the orbital excitation picture. A crucial prediction is that $Y(4260)$ should decay predominantly in $D_s\bar{D}_s$. The $Y(4260)$ should also be seen in $B$ non-leptonic decays in association with one kaon. We consider the full nonet of related four-quark states and their predicted properties. Finally, we comment on a possible narrow resonance in the same channel.

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In a series of exciting experiments, BELLE and BaBar have discovered several states that, although decaying in charmonium plus pions, do not seem to fit the $J/\psi\pi\pi$ picture, in particular the $X(3872)$ and $X(3940)$ states.

In a recent paper [1] we have pointed out that the properties of the new states can be well explained if they are $S$-wave diquark-antidiquark bound states with the composition $(q = u, d)$: $[(cq)\bar{(cq)}]_{S\text{-wave}}$. An alternative scenario is the molecular picture where the $X(3872)$ would be a $D^0D^{*0}$ bound state. A crucial difference between the two alternatives is that colored objects in a rising confining potential, such as diquarks, should exhibit a series of orbital angular momentum excitations. This is clearly at variance with the molecular picture. Colorless objects bound by a short range potential should have a very limited spectrum, possibly restricted to $S$-wave states only.

In this note we would like to propose that the first orbital excitation of a diquark-antidiquark state may have indeed been found in the state $Y(4260)$ recently announced by the BaBar collaboration [2]. We discuss the properties of the new state in this framework and spell out a few distinctive predictions. The most revealing among them is that the dominant decay mode of $Y(4260)$ should be in $D_s\bar{D}_s$ pairs. We shall also briefly discuss other states implied by the scheme and their properties. We comment on the possibility of an additional narrow state.

The $Y(4260)$ is observed by BaBar in $e^+e^-$ annihilation, in association with an Initial-State-Radiation photon, which implies $J^{PC} = 1^{--}$. The particle has a width of about 90 MeV and it is seen to decay in $J/\psi\pi^+\pi^-$. The $\pi^+\pi^-$ mass distribution peaks around 1 GeV, consistently with a decay into $J/\psi f_0(980)$. BaBar reports the value [2]:

$$\Gamma(Y \to e^+e^-) \times Br(Y \to J/\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7} \text{ eV}$$

The diquark-antidiquark assumption together with the negative parity call for at least one unit of orbital angular momentum. In addition, the decay into $f_0(980)$, which fits the $[(sq)[\bar{s}\bar{q}]_{S\text{-wave}}$ hypothesis [3], suggests a $[cs][\bar{s}\bar{c}]$ composition. All considered, we are led to the following assumption for the $Y(4260)$:

$$Y(4260) = (c\bar{s})_{s=0}[\bar{c}\bar{s}]_{s=0}p_{\text{-wave}}$$

with both diquarks in a $\bar{3}$ color state.

As discussed in [1] we expect diquarks involving charmed quarks to be bound also in states with non-vanishing spin (bad diquarks [4], with $S = 1$). Thus, several other states with $J^{PC} = 1^{--}$ are possible and one would expect the physical $Y(4260)$ to be a linear superposition of all such states. The state in (2) is supposedly the lowest lying among them and we restrict to it in this first analysis.

Following [1], a simple mass formula for the $Y$ state can be given as follows:

$$M_Y = 2m_{[cq]} + 2(m_s - m_q) - 3\kappa_{cs} + B_c \left( \frac{L(L+1)}{2} \right).$$

$m_{[cq]}$ is the mass of the heavy-light diquark as computed in Ref. [1], i.e., $m_{[cq]} = 1933$ MeV, $m_q$ and $m_s$ are the constituent up and strange quark masses, respectively. A fit to the lowest lying meson and baryon masses, as reported in [1], gives $m_s - m_q = 185$ MeV. Spin-spin
interactions are described by the Hamiltonian:

$$H_{\text{spin-spin}} = 2\kappa_{cs}(\vec{S}_c \cdot \vec{S}_s + \vec{S}_{\bar{c}} \cdot \vec{S}_{\bar{s}})$$

and $-3\kappa_{cs}$ is its eigenvalue in the $S = 0$ state. The value of $\kappa_{cs}$ is obtained from a fit to the charmed strange baryon spectrum and is reported in [1] as $(\kappa_{cs})^2 = 25$ MeV. In Eq. (3) we are neglecting spin-spin interactions between quarks and antiquarks (because of the angular momentum barrier which separates the diquark from the antidiquark) and the spin-orbit interaction (because of $S = 0$). In fact, the spin-orbit interaction can mix the good diquark, $S = 0$, with the bad diquark, $S = 1$, giving however only a second order correction to the mass that we provisionally neglect. These considerations lead to:

$$M_Y = 4160 + B_c \left( \frac{L(L+1)}{2} \right)$$

which leaves $\sim 100$ MeV for the orbital term, the only new ingredient with respect to Ref. [1]. We try different ways to estimate $B_c$ from the corresponding terms in $qq$ spectrum. We find somewhat different results, which gives an idea of the theoretical error involved.

We describe the masses of the $S = 1, L = 0, 1$ states $\rho(770), a_1(1230), a_2(1320)$ with the equation:

$$M(S = 1, L, J) = K + 2A_q \vec{S} \cdot \vec{L} + B_q \frac{L(L+1)}{2}. \quad (6)$$

One finds at once:

$$B_q = \frac{a_1 + a_2 - 2\rho}{2} = 0.495 \text{ GeV}. \quad (7)$$

For charm and beauty we take the difference between the lowest $S = 1, L = 0$ state and the center of $S = 1, L = 1$ mass spectrum and find:

$$B_{J/\psi} = 425 \text{ MeV}; \quad B_T = 440 \text{ MeV}. \quad (8)$$

For the quantum rotator $B \propto (mR^2)^{-1}$, with $R$ the radius of the bound state. Assuming the same radius and using $m_c = 1.3 \text{ GeV}$ and $m_{[cs]} = 2.1 \text{ GeV}$ as given above, we obtain from the light quark case:

$$B_c = \frac{m_q}{m_{[cs]}} \times 495 \simeq 120 \text{ MeV} \quad (9)$$

(scaling from charmonium we would get $B_c \simeq 260 \text{ MeV}$).

An extreme alternative is to consider the diquark as a single constituent quark and scale the orbital terms as appropriate for Coulomb bound states. In this case, $B$ scales like $\frac{m_c}{(R^2 M)^{-1}}$ and $R = (\alpha_s M)^{-1}$ so that

$$B \propto \alpha_s^2 M. \quad (10)$$

This formula does not reproduce the values of $B_q, B_{J/\psi}, B_T$ simultaneously. Using $\Lambda_{\text{QCD}} = 190 \text{ MeV}$ we find $B_{J/\psi} \simeq 340 \text{ MeV}, B_T \simeq 500 \text{ MeV}$; for a slightly larger $\Lambda_{\text{QCD}} = 270 \text{ MeV}$ we find $B_{J/\psi} \simeq 135 \text{ MeV}, B_T \simeq 170 \text{ MeV}$. In correspondence $B_c \simeq 370 \text{ MeV}$ and $134 \text{ MeV}$ respectively. The experimental $Y$ mass clearly prefers a wider structure than charmonium but otherwise the orbital excitation picture is compatible within large theoretical errors:

$$M_Y^{\text{th}} = 4330 \pm 70 \text{ MeV}. \quad (11)$$

Given the quantum numbers $J^{PC} = 1^{--}$, the state in Eq. (2) should decay strongly into a pair of mesons with open charm. The quark composition in (2) implies a definite preference for charm-strange states:

$$\Gamma_Y(D_s\bar{D}_s) >> \Gamma_Y(D\bar{D}) \quad (12)$$

Dominant $D_s\bar{D}_s$ decay is quite a distinctive signature of the validity of the present model.

Quark diagrams corresponding to the $D_s\bar{D}_s$ and to the $J/\psi f_0(980)$ decays are reported in Fig. 1. Unlike the case of the $X(3872)$, the latter decay is not the dominant one. Assuming a partial width similar to the total
width of $X(3872)$, namely a few MeV’s, one predicts a branching ratio for the $J/ψ f_0(980)$ channel in the order of $10^{-1} \div 10^{-2}$. The observation of BaBar, Eq. 4, therefore implies for the $Y(4260)$ a leptonic width of $50 \div 500$ eV, which is not unlikely for the one-photon production of such a complex state and consistent with the non-observation of this resonance in multihadron $e^+e^-$ production around $E = 4$ GeV [6].

The $Y(4260)$ should be seen in $B^-$ and $B^0$ weak non-leptonic decays, see the quark diagrams in Fig. 2, with:

$$\Gamma(B^0 \rightarrow Y K_S) = \frac{1}{2} \Gamma(B^- \rightarrow Y K^-). \quad (13)$$

Replacing the strange quark/antiquark with light quarks/antiquarks one obtains a full nonet of $J^{PC} = 1^{−−}$ mesons. From the charm baryon spectrum one finds [1]:

$$\left( \kappa_{cs} \right)_S \simeq \left( \kappa_{cq} \right)_S,$$

so that the levels in the nonet are equispaced by $\simeq 185$ MeV ($s$=strangeness):

$$M_{Y}(I=0; s=0) = 3.91 \text{ GeV}; \quad M_{Y}(I=1/2; s=\pm 1) = 4.10 \text{ GeV}. \quad (14)$$

The neutral members of the non-strange complex should be seen in $e^+e^-$ annihilation and in $B$ non-leptonic decays (produced by diagrams like that in Fig. 2 with the $s\bar{s}$ pair replaced by $u\bar{u}$ or $d\bar{d}$). Dominant decay modes are in $D\bar{D}$. Similar to the $X(3872)$ case, a significant isospin breaking in the wave function of the non-strange states can be expected. This should reflect in unequal branching ratios of each mass eigenstate in $D^+D^−$ versus $D^0\bar{D}^0$. In the limiting case of pure $[[cu][\bar{c}\bar{u}]]_{P−\text{wave}}$ and $[[cd][\bar{c}\bar{d}]]_{P−\text{wave}}$ the first would decay in $D^0\bar{D}^0$ only and the second in $D^+D^−$. Decays into $J/ψ\pi^+\pi^−$ are expected to occur as well, with $\pi^+\pi^−$ peaking at the $\sigma(480)$ mass (restricted to the $I = 0$ state, if isospin would be conserved).

The BaBar data suggest, although inconclusively, that there may be a considerably more narrow satellite line at a mass $M \sim 4330$ MeV. We observe that this mass difference is of the order of the spin-spin interaction. Indeed, if one calls into play bad diquark states with $S = 1$ there are several additional $1^{−−}$ states with the same quark composition, $(cs)(\bar{c}\bar{s})$. Among them, the state with both diquark and antidiquark spins in $S = 1$, combined to $S_{\text{tot}} = 2$. This state projects only on spin one $c\bar{s}$ and $s\bar{c}$ states. In the (not unrealistic) limit where the spin of the $s$ quark is a good quantum number, such state could decay only into $D_s^0\bar{D}_s^0$ pairs, with substantial reduction of its decay width.

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