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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 ($[cs][\bar{c}\,\bar{s}]$). 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 nonleptonic 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 $c\bar{c}$ 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 ($q = u, d$): $[(cq)(\bar{c}\,\bar{q})]_{S-\mathrm{wave}}$. An alternative scenario is the molecular picture where the $X(3872)$ would be a $D^0\bar{D}^{0*}$ 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 paper 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]

$$\Gamma(Y \to e^+e^-) \times Br(Y \to J/\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7}\ \mathrm{eV} \tag{1}$$

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 $([sq][\bar{s}\,\bar{q}])_{S-\mathrm{wave}}$ hypothesis [3], suggests a $[cs][\bar{c}\,\bar{s}]$ composition. All considered, we are led to the following assumption for the $Y(4260)$:

$$Y(4260) = ([cs]_{S=0}[\bar{c}\,\bar{s}]_{S=0})_{P-\mathrm{wave}} \tag{2}$$

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

As discussed in [1] we expect diquarks involving charmed quarks to be bound also in states with nonvanishing 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:

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

$m_{[cq]}$ 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

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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

$$H_{\text{spin-spin}} = 2\kappa_{cs}(\vec{S}_c \cdot \vec{S}_s + \vec{S}_{\bar{c}} \cdot \vec{S}_{\bar{s}}) \tag{4}$$

and $-3\kappa_{cs}$ is its eigenvalue in the $S = 0$ state. The value of κ_{cs} is obtained from a fit to the charmed strange baryon spectrum and is reported in [1] as $(\kappa_{cs})_{\bar{3}} = 25$ 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

$$M_Y = 4160 + B_c\left(\frac{L(L+1)}{2}\right) \tag{5}$$

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 $q\bar{q}$ 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

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

One finds at once

$$B_q = \frac{a_1 + a_2 - 2\rho}{2} = 0.495 \text{ GeV}, \tag{7}$$

where letters denote particle masses.

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

$$B_{J/\psi} = 425 \text{ MeV}; \qquad B_\Upsilon = 440 \text{ MeV}. \tag{8}$$

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

$$B_c = \frac{m_q}{m_{[cs]}} 495 \simeq 120 \text{ MeV} \tag{9}$$

(scaling from charmonium we would get $B_c \simeq 260$ 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 [5] $(R^2M)^{-1}$ and $R = (\alpha_s M)^{-1}$ so that

$$B \propto \alpha_s^2 M. \tag{10}$$

This formula does not reproduce the values of B_q, $B_{J/\psi}$, B_Υ simultaneously. Using B_q of Eq. (7) and $\Lambda_{\text{QCD}} = 190$ we find $B_{J/\psi} \simeq 340$ MeV, $B_\Upsilon \simeq 500$ MeV; for a slightly larger $\Lambda_{\text{QCD}} = 270$ MeV we find $B_{J/\psi} \simeq 135$ MeV, $B_\Upsilon \simeq 170$ MeV. In correspondence $B_c \simeq 370$ MeV and 134 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.

$$M_Y^{\text{th.}} = 4330 \pm 70 \text{ MeV}. \tag{11}$$

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.

$$\Gamma_Y(D_s\bar{D}_s) \gg \Gamma_Y(D\bar{D}) \tag{12}$$

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 $J/\psi f_0(980)$ channel in the order of 10^{-1}–10^{-2}. The observation of *BABAR*, Eq. (1), therefore implies for the $Y(4260)$ a leptonic width of 50–500 eV, which is not unlikely for the one-photon production of such a complex state and consistent with the nonobservation 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 nonleptonic decays, see the quark diagrams in Fig. 2, with

$$\Gamma(B^0 \to YK_S) = \frac{1}{2}\Gamma(B^- \to YK^-). \tag{13}$$

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]

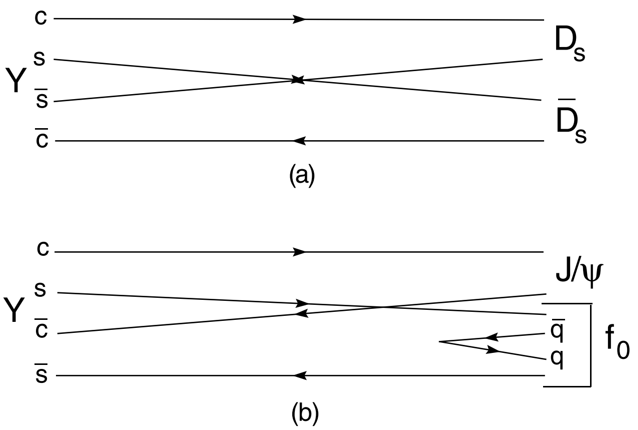

FIG. 1. (a) Quark diagram for the dominant decay channel to $D_s\bar{D}_s$ see Ref. [3]. (b) Decay amplitude for $Y \to J/\psi f_0(980)$ under the assumption that both Y and f_0 are four-quark states.

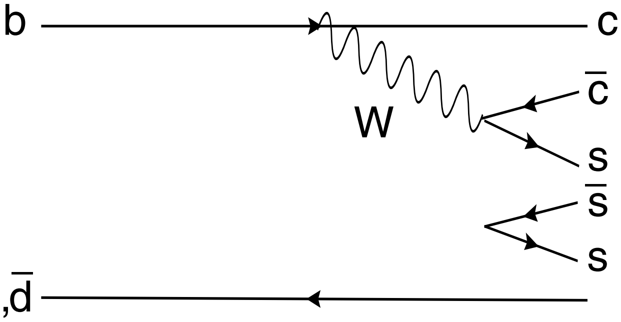

FIG. 2. Quark diagram for the weak decay of a $B^{-,0}$ meson into YK^- and YK_S. Kaons can be obtained in two independent ways by combining the spectator antiquark with a strange quark from the weak vertex or from the sea pair.

$(\kappa_{cs})_{\bar{3}} \simeq (\kappa_{cq})_{\bar{3}}$, so that the levels in the nonet are equispaced by $\simeq$ 185 MeV (s = strangeness).

$$\begin{aligned} M_{Y(I=0,1;s=0)} &= 3.91\ \text{GeV}; \\ M_{Y(I=1/2;s=\pm1)} &= 4.10\ \text{GeV}. \end{aligned} \tag{14}$$

The neutral members of the nonstrange complex should be seen in e^+e^- annihilation and in B nonleptonic 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 nonstrange 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 $([cu][\bar{c}\,\bar{u}])_{\text{P-wave}}$ and $([cd][\bar{c}\,\bar{d}])_{\text{P-wave}}$ the first would decay in $D^0\bar{D}^0$ only and the second in D^+D^-. Decays into $J/\psi\pi^+\pi^-$ 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 $D_s^*\bar{D}_s^*$ pairs, with substantial reduction of its decay width.

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