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# *B* decays as spectroscopy for charmed four-quark states

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## Abstract

The  $D_s(2320)$  state recently observed by BaBar in the  $D_s^+\pi^0$  channel may be the first of a host of  $cq\bar{q}\bar{q}$  four-quark states. We give a phenomenological account of the masses and decay modes. The isosinglet  $D_s(2320)$  state is the only narrow one, dominated by the observed isospin violating decay and less than  $\sim 100$  keV in width. All other states are expected to decay hadronically. Notable resonances are in doubly charged  $D_s^+\pi^+$ ,  $D^+K^+$ , wrong pairing  $D^+K^-$ , and also  $D_s^+K^-$ ,  $D\eta$  channels. We propose  $B$  decays as searching ground for such 4-quark states, which recoil against  $\bar{D}^{(*)}$  meson from  $B$  decay, or  $\pi^+\bar{D}^{(*)}$ ,  $\bar{K}$  mesons from  $\bar{B}$  decay. Exotic  $qc\bar{c}\bar{q}$  charmonia could also be produced, and may be behind the slow  $J/\psi$  bump in inclusive  $B \rightarrow J/\psi + X$  decay.

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## 1. Introduction

BaBar experiment [1] has recently discovered a new narrow state, the  $D_s^+(2320)$ , decaying into  $D_s^+\pi^0$ . The width is consistent with experimental resolution. It is lighter than expected from potential models [2], considerably below the observed  $D_{s1}^+(2536)$  and  $D_{sJ}^+(2573)$  believed to be the  $1^+$  and  $2^+$   $P$ -wave states with  $j = 3/2$  for the  $s$  quark spin-orbit angular momentum. The  $D_s^+\pi^0$  decay angular distribution is flat. These facts suggest a  $J^P = 0^+$  assignment, which forbids  $D_s^+(2320) \rightarrow D_s^+\pi\pi$  transitions. Since  $D_s^+(2320) \rightarrow D_s^+\pi^0$  would violate isospin if it is a normal  $c\bar{s}$  meson, this is consistent with its nar-

rowness. The BaBar experiment has also searched for  $D_s^+(2320) \rightarrow D_s^+\gamma$  and  $D_s^+\gamma\gamma$  electromagnetic decays, which are so far absent. A possible  $D_s^{*+}\pi^0$  state could exist at 2460 MeV, but is not yet established. It was therefore suggested that either the 2-quark potential models should be revised, or the  $D_s^+(2320)$  could be a four-quark state.

A light  $0^+$  hadron nonet exists and could be interpreted as 4-quark states. The  $a_0(980)$  and  $f_0(980)$  mesons are often viewed as  $K\bar{K}$  molecules, which accounts for their near degeneracy with  $2m_K$ . However, the recent observation of  $B^- \rightarrow f_0(980)K^-$  decay [3,4] (and possibly  $B^- \rightarrow a_0(980)K^-$ ) casts doubt to this picture, since it is hard to conceive a loosely bound state to be ejected in  $B$  decay with 2.5 GeV energy. Furthermore, two experiments, E791 at Fermilab Tevatron [5], and BES at BEPC [6], have claimed the

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possible existence of a scalar resonance,  $\kappa$ , in the  $K\pi$  channel. Together with the resurrected  $\sigma$  ( $f_0(600)$ ), one has an isospin triplet, two doublets and two singlets. They could be composed of  $qq\bar{q}\bar{q}$  with  $q = u, d, s$ , as we shall see.

It has been argued [7] that a strong attraction between  $(qq)_3^*$  and  $(\bar{q}\bar{q})_3$  [8,9], where  $3^*$  and  $3$  here refer to color, and the absence of the orbital angular momentum barrier in the  $S$ -wave 4-quark state, may explain why the scalar nonet formed by  $\sigma$ ,  $\kappa$ ,  $f_0(980)$  and  $a_0(980)$  is lighter than the conventional  $q\bar{q}$  nonet composed of  $f_0(1370)$ ,  $a_0(1450)$ ,  $K_0^*(1430)$  and  $f_0(1500)/f_0(1710)$ . By the same token, it is likely that a scalar  $cn\bar{n}\bar{s}$  4-quark state, where  $n = u, d$ , will be lighter than the  $0^+$   $P$ -wave  $c\bar{s}$  state, where a typical potential model prediction gives 2487 MeV [2]. Hence, the  $cn\bar{n}\bar{s}$  state could lie below the  $DK$  threshold and decay only to  $D_s^+\pi^0$  final state. One is thus motivated to consider the  $cq\bar{q}\bar{q}$  4-quark meson scenario, originally suggested by Lipkin [10], and explore its possible multiplet structure. In this Letter we pursue such a direction, and in particular propose  $B$  decays as a possible avenue to uncover a host of such states. The  $B$  meson acts as a “filter” for background suppression, which should be compared with direct search of broad resonances in charm fragmentation.

## 2. The scalar $qq\bar{q}\bar{q}$ and $cq\bar{q}\bar{q}$ multiplets

Taking cue from the light hadron nonet, one considers the  $3^*$  under  $SU(3)$  formed by  $qq$ , i.e.,  $ud$ ,  $us$  and  $ds$  where the flavors in the pair are distinct. Combining with the  $3$  of  $\bar{q}\bar{q}$ , one therefore gets an  $8$  plus a  $1$ . The  $\kappa$  state, if it exists at all, is an isodoublet that can be written as  $[udd\bar{s}]^+$  and  $[du\bar{u}\bar{s}]^0$ , plus its antiparticle, where we have suppressed all (anti-)symmetrizations of quark or quark–anti-quark pairings. The charged components for  $a_0$  can be written as  $a_0^+ = [sud\bar{s}]^+ = (a_0^-)^*$ , with the neutral component written as  $a_0^0 = [s(n\bar{n})-\bar{s}]^0$  to respect isospin  $((n\bar{n})_\pm \equiv (u\bar{u} \pm d\bar{d})/\sqrt{2})$ . We write  $f_0 = [s(n\bar{n})+\bar{s}]^0$  which is orthogonal to  $a_0^0$  and is an isosinglet. This leaves  $\sigma = [udd\bar{u}]^0$  which is also a singlet. Although  $f_0$  and  $\sigma$  (and for that matter,  $a_0$ ) could mix, there is no evidence for  $f_0$  and  $\sigma$  to deviate from the flavor

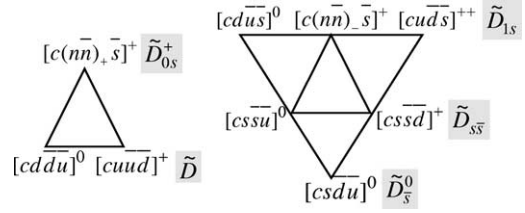


Fig. 1. The  $3^*$  and  $6$  multiplets of  $cq\bar{q}\bar{q}$  mesons, where  $cq = cu, cd, cs$ , and  $\bar{q}\bar{q} = \bar{d}\bar{s}, \bar{u}\bar{s}, \bar{u}\bar{d}$ .

content we assign. The mass pattern supports isospin multiplets split by their  $s$  or  $\bar{s}$  content.

Extending to the  $3$  constructed from  $cq$ , one finds the  $cq\bar{q}\bar{q}$  4-quark mesons form a  $3^*$  and a  $6$ . Unlike Suzuki and Tuan [11], we think it is the isospin multiplets that matter, with splittings between multiplets determined more by  $s$  or  $\bar{s}$  content. Although  $3^* - 6$  splitting cannot be ruled out, this is the assumption we shall follow. In the notation of Lipkin, Suzuki and Tuan, the singlet of  $3^*$  is denoted as  $\tilde{F}_X^+$ , while the triplet and singlet of  $6$  are denoted  $\tilde{F}_I$  and  $\tilde{F}_S^0$ ; we shall denote these as  $\tilde{D}_{0s}^+ = [c(n\bar{n})+\bar{s}]^+$ ,  $\tilde{D}_{1s} = ([cd\bar{u}\bar{s}]^0, [c(n\bar{n})-\bar{s}]^+, [cud\bar{s}]^{++})$  and  $\tilde{D}_s^0 = [cs\bar{u}\bar{d}]^0$ . Note that we have retained the tilde notation of Lipkin for 4-quark states, but dropped  $F$  since it is no longer in use. Instead, we have extended the convention for  $D_s^+$  mesons, e.g., the  $\tilde{D}_{s\bar{s}}$  state has  $c$  and  $s$  flavor, rather than  $\bar{s}$ ! Following this convention, and our assumption that the mass eigenstates are determined by its (absence of)  $s/\bar{s}$ ,  $s\bar{s}$  content, we denote the two doublets as  $\tilde{D} = ([cd\bar{d}\bar{u}]^0, [cu\bar{u}\bar{d}]^+)$  and  $\tilde{D}_{s\bar{s}} = ([cs\bar{s}\bar{u}]^0, [cs\bar{s}\bar{d}]^+)$ , where we assume ideal mixing. These states, put in the form of  $3^*$  and  $6$ , are illustrated in Fig. 1.

The  $\tilde{D}_{0s}^+$  state is an isosinglet, and can be identified with the narrow  $D_s(2320)$  state found by BaBar. We shall argue that all other states decay hadronically. But we need to first develop some picture on mass splittings. Besides the  $\tilde{D}_{0s}^+$  state and the aforementioned  $\tilde{D}_s^0$  having  $cs$  rather than  $c\bar{s}$  flavor, another notable state is the exotic doubly charged scalar  $\tilde{D}_{1s}^{++}$ .

## 3. Masses, decay modes and widths

This section should be viewed as providing only guesstimates.

As stressed in previous section, we treat isomultiplet masses which are split by its  $s$  or  $\bar{s}$  quark content, rather than work on SU(3) multiplet masses. We shall ignore isospin splittings within an isomultiplet. We therefore expect the mass ordering of  $m_{\tilde{D}} < m_{\tilde{D}_{1s}} \simeq m_{\tilde{D}_{\bar{s}}} < m_{\tilde{D}_{s\bar{s}}}$ , where  $m_{\tilde{D}_{1s}} - m_{\tilde{D}_{0s}}$  is susceptible to a possible  $6-3^*$  splitting, which we ignore.

We illustrate with a picture of “naive constituent diquark model” for 4-quark mesons, in analogy to the usual Naive Quark Model of normal mesons, just for counting purposes. Let us take

$$\begin{aligned} m_{nn} &= m_0, & m_{sn} &= m_0 + \Delta m_0, \\ m_{cn} &= m, & m_{cs} &= m + \Delta m, \end{aligned} \quad (1)$$

where  $n = u, d$ , and we allow for  $\delta m = \Delta m - \Delta m_0$  to be nonzero, since the  $cs$  and  $ns$  pairing may have different (QCD) dynamics. We then find that

$$\begin{aligned} m_{\tilde{D}} &\sim m + m_0 \sim 2100\text{--}2200 \text{ MeV}, \\ m_{\tilde{D}_{1s}} &\sim m + m_0 + \Delta m_0 \sim 2320 \text{ MeV}, \\ m_{\tilde{D}_{\bar{s}}} &\sim m + m_0 + \Delta m \sim 2320 \text{ MeV} + \delta m, \\ m_{\tilde{D}_{s\bar{s}}} &\sim m + m_0 + \Delta m_0 + \Delta m \sim 2500 \text{ MeV} + \delta m, \end{aligned} \quad (2)$$

which realizes the above ordering, and allows  $\tilde{D}_{1s}$  to be heavier or lighter than  $\tilde{D}_{\bar{s}}$ . The assignment of  $m_{\tilde{D}_{1s}} \sim 2320 \text{ MeV}$  is clear. Let us explain the other numbers.

Applying Eq. (1) to the  $qq\bar{q}\bar{q}$  scalar nonet, we find  $m_\sigma \sim 2m_0$ ,  $m_\kappa \sim 2m_0 + \Delta m_0$ ,  $m_{a_0, f_0} \sim 2m_0 + 2\Delta m_0$ , where the degeneracy of  $a_0$  and  $f_0$  is realized. The splitting  $m_\kappa - m_\sigma \sim 200 \text{ MeV}$  vs.  $m_{a_0/f_0} - m_\kappa \sim 180 \text{ MeV}$  is reasonable. We note, however, that the 4-quark  $\sigma$  state could be affected by chiral symmetry breaking which leads to the pion being a pseudo-Goldstone boson. Mindful of this, we take  $m_0 \sim 300 \text{ MeV}$ ,  $\Delta m_0 \sim 180 \text{ MeV}$ . With these numbers as input we arrive at the numerical suggestions in Eq. (2). Note that this numerology implies  $m = m_{cn} \sim 1800 \text{ MeV}$ , which is higher than the naive  $m_c$  constituent mass. This is in contrast with  $m_{nn} \sim m_n$  and  $m_{sn} \sim m_s$ , and is one of the reasons behind our treatment of  $\delta m = \Delta m - \Delta m_0 = (m_{cs} - m_{cn}) - (m_{sn} - m_{nn})$  as potentially nonzero. From this trend, we speculate that  $\delta m > 0$ , hence  $m_{\tilde{D}_{\bar{s}}} \gtrsim m_{\tilde{D}_{1s}}$ , and  $m_{\tilde{D}_{s\bar{s}}}$  is probably above 2500 MeV. With these masses, we now discuss decay modes.

By taking  $m_{\tilde{D}_{1s}} \sim 2320 \text{ MeV}$ , we identify the isosinglet  $\tilde{D}_{0s}$  with the narrow BaBar state. Since this is below  $DK$  threshold, only the  $D_s^+ \pi^0$  isospin violating decay is allowed, which is consistent with what is observed. Electromagnetic decays are often on equal footing with isospin violating decays, but BaBar seems to find these to be subdominant. It is of interest to understand this.

The isospin-violating strong decay  $\tilde{D}_{0s}^+ \rightarrow D_s^+ \pi^0$  can proceed via  $\tilde{D}_{0s}^+ \rightarrow D_s^+ \eta(\eta')$  followed by  $\eta(\eta') - \pi^0$  mixing [12]. We consider the flavor mixing of  $\eta_n$  and  $\eta_s$  defined by  $\eta_n = (1/\sqrt{2})(u\bar{u} + d\bar{d})$  and  $\eta_s = s\bar{s}$ . The wave functions of the  $\eta$  and  $\eta'$  are then given by

$$\begin{aligned} \eta &= \eta_n \cos \phi - \eta_s \sin \phi, \\ \eta' &= \eta_n \sin \phi + \eta_s \cos \phi. \end{aligned} \quad (3)$$

A phenomenological analysis of many different experimental processes indicates  $\phi = 39.3^\circ$  [13].

The isospin violating term induced by the  $u$  and  $d$  quark mass difference is

$$\mathcal{L} = \frac{1}{2}(m_d - m_u)(\bar{u}u - \bar{d}d). \quad (4)$$

The strong coupling for  $\tilde{D}_{0s}^+ \rightarrow D_s^+ \pi^0$  then reads

$$\begin{aligned} g_{\tilde{D}_{0s}^+ D_s^+ \pi^0} &= \left( \frac{m_d - m_u}{m_\eta^2 - m_\pi^2} \sin^2 \phi + \frac{m_d - m_u}{m_{\eta'}^2 - m_\pi^2} \cos^2 \phi \right) \\ &\quad \times \frac{1}{2} g_{\tilde{D}_{0s} D_s^+ \eta_n} \langle \pi^0 | \bar{u}u - \bar{d}d | \eta_n \rangle, \end{aligned} \quad (5)$$

where  $\langle \pi^0 | \dots | \eta_n \rangle$  can be evaluated as [14]

$$\langle \pi^0 | \bar{u}u - \bar{d}d | \eta_n \rangle = \langle \pi^0 | \bar{u}u + \bar{d}d | \pi^0 \rangle = 2v, \quad (6)$$

with  $v = -2\langle \bar{q}q \rangle / f_\pi^2 = m_\pi^2 / (m_u + m_d)$ . We shall make two estimates of the strong coupling  $g_{\tilde{D}_{0s} D_s^+ \eta_n}$ . First, it can be extracted from the measured width of  $\kappa$  whose coupling is  $g_{\kappa K \pi} = \sqrt{3/2} g_0$  in terms of  $g_{\tilde{D}_{0s} D_s^+ \eta_n} = g_0$  based on SU(4) symmetry. Using  $\Gamma_\kappa \approx 400 \text{ MeV}$ , we obtain  $g_{\tilde{D}_{0s} D_s^+ \eta_n} \approx 4.4 \text{ GeV}$  and hence

$$\Gamma(\tilde{D}_{0s}^+ \rightarrow D_s^+ \pi^0) \approx 11 \text{ keV}. \quad (7)$$

Second, in the 2-quark model for  $D_0^*$ , the  $P$ -wave scalar, the  $D_0^* D \pi$  coupling has been estimated in the framework of QCD sum rules by two different methods, giving  $g_{D_0^* D \pi} = (6.3 \pm 1.2) \text{ GeV}$  and

(11.5 ± 4.0) GeV [15]. Since  $D_0^* \rightarrow D\pi$  is OZI suppressed relative to  $\tilde{D}_{0s}^+ \rightarrow D_s^+\eta_n$ , it is expected that  $g_{\tilde{D}_{0s}^+ D_s^+ \eta_n} > g_{D_0^* D\pi}$ . Taking  $g_{\tilde{D}_{0s}^+ D_s^+ \eta_n} = 15$  GeV as a representative value, we are led to  $\Gamma(\tilde{D}_{0s}^+ \rightarrow D_s^+\pi^0) = 130$  keV. In any rate, it is fair to conclude that the width of  $\tilde{D}_{0s}^+$  is smaller than 1 MeV and lies in between 10 and 100 keV.

For the radiative decay  $\tilde{D}_{0s}^+ \rightarrow D_s^+\gamma\gamma$ , three different contributions have been considered by [11]:

- (i) two-photon transition between four-quark states,
- (ii) two-photon emission by pair annihilation, and
- (iii) two photon emission from  $\bar{s}$  quark.

A naive estimate of two-photon transition between  $n\bar{n}$  and  $n\bar{n}$  states are [11]

$$\Gamma(\tilde{D}_{0s}^+ \rightarrow D_s^+\gamma\gamma) \simeq \frac{1}{12\pi} \frac{\alpha^2 \Delta^5}{M^4}, \quad (8)$$

where  $\Delta = m_{\tilde{D}_{0s}^+} - m_{D_s}$  and  $M$  is the constituent quark mass of  $u$  and  $d$ . Numerically,  $\Gamma(\tilde{D}_{0s}^+ \rightarrow D_s^+\gamma\gamma) \simeq 0.48$  keV. For two-photon emission by pair annihilation, it can proceed via  $\tilde{D}_{0s}^+ \rightarrow D_s^+\eta$  followed by  $\eta \rightarrow \gamma\gamma$ . Current algebra leads to [11]

$$\Gamma(\tilde{D}_{0s}^+ \rightarrow D_s^+\gamma\gamma) \approx \frac{1}{192\pi^3} \left( \frac{\alpha}{8\pi f_\pi} \right)^2 \frac{\Delta^9}{f_\pi^2 m_\eta^4}, \quad (9)$$

giving  $\sim 4 \times 10^{-5}$  keV, which is further suppressed. We conclude that  $\tilde{D}_{0s}^+$  decay being dominated by the isospin-violating strong decay is reasonable.

We have assumed that  $m_{\tilde{D}_{1s}} \simeq m_{\tilde{D}_{0s}}$  by resorting to quark content and some vague isospin arguments. If this holds, since isospin splittings are rarely more than 10 MeV, one is still below the  $m_D + m_K$  threshold, but the  $\tilde{D}_{1s}^+ \rightarrow D_s^+\pi$  decay is now an allowed strong decay, with a typical width of 100 MeV or more. Note that this contains three modes:  $\tilde{D}_{1s}^{++} \rightarrow D_s^+\pi^+$ ,  $\tilde{D}_{1s}^+ \rightarrow D_s^+\pi^0$ , and  $\tilde{D}_{1s}^0 \rightarrow D_s^+\pi^-$ . The doubly charged scalar resonance would be astounding. We caution that there may still be some  $3^*-6$  splitting, which would likely push the  $6$  higher than the  $3^*$  [11]. This could open up the  $DK$  channels:  $\tilde{D}_{1s}^{++} \rightarrow D^+K^+$ ,  $\tilde{D}_{1s}^+ \rightarrow D^+K^0$  and  $D^0K^+$ , and  $\tilde{D}_{1s}^0 \rightarrow D^0K^0$ . The doubly charged  $D^+K^+$  scalar resonance would again be the most astounding.

The  $\tilde{D}$  doublet  $\sim 2100$ – $2200$  MeV in mass would decay into  $D\pi$ , just like a normal  $D^*$  meson, but with

flat angular distributions, and a few 100 MeV in width. They should in principle be distinct from the observed  $D_1(2420)$  and  $D_2(2460)$  states since they are lower in mass. Since the  $D\pi$  mass spectrum has been studied for some time, it may be difficult to identify such scalar resonances, but efforts should be renewed.

The  $\tilde{D}_{s\bar{s}}$  is a second  $D$ -like doublet with  $s\bar{s}$  content, which pushes its mass above 2500 MeV, as we have argued in Eq. (2). Thus, it is above  $D_s^+\bar{K}$  threshold of  $\sim 2460$  MeV. Besides the  $\tilde{D}_{s\bar{s}} \rightarrow D_s^+\bar{K}$  channel, the  $D\eta$  (and perhaps  $D\pi$ ) channel should be subdominant, with a slightly lower threshold, and could provide a useful crosscheck.

We finally reach the  $\tilde{D}_{\bar{s}}$  exotic singlet with both  $c$  and  $s$  flavor. We first offer another argument that  $\delta m > 0$  in Eq. (2). Suppose the opposite is true. Since  $\tilde{D}_{0s}$  is below  $DK$  threshold, so would  $\tilde{D}_{\bar{s}}$  be below  $D\bar{K}$  threshold. Inspection of the  $\tilde{D}_{\bar{s}}$  quark flavor composition, it contains all four distinct flavors, hence it can then undergo only *weak* decay. Indeed, this was one of the original excitations of Lipkin [10], and of Suzuki and Tuan [11]. But given that 20–25 years have elapsed, we find it highly unlikely that we have missed a semi-stable, weakly decaying neutral  $D$ -like meson at  $\sim 2300$  MeV. Thus, we argue that  $m_{\tilde{D}_{\bar{s}}} > m_D + m_{\bar{K}}$ , and one should search via  $\tilde{D}_{\bar{s}} \rightarrow D^0\bar{K}^0$  or  $D^+K^-$  with a strong width of 100 MeV or more. Note the unusual pairing of  $D$  and  $\bar{K}$  mesons.

The upshot of our discussion is that, BaBar found the single narrow state which derives from its low mass, allowing it to decay only via a suppressed isospin violating channel. All other  $cq\bar{q}\bar{q}$  scalar states undergo strong decay hence would be considerably broader.

#### 4. $B$ decays as $\tilde{D}_X$ spectroscopy

All states except the  $D_s(2320)$  already seen by BaBar would likely be broad states. But to convince oneself of the 4-quark nature, it would be necessary to uncover a major portion of the full spectroscopy. The strongly decaying nature makes further direct search in charm fragmentation not so optimistic. Instead, we propose  $B$  decays as a “spectroscopy” through which one may search for such states with lower background.

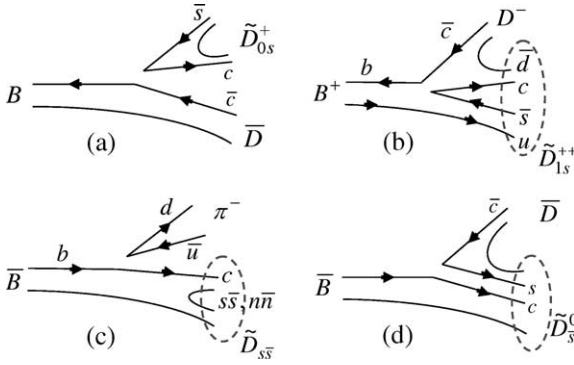


Fig. 2. Diagrams for (a)  $B \rightarrow \bar{D} \tilde{D}_{0s}^+$ , (b)  $B^+ \rightarrow D^- \tilde{D}_{1s}^{++}$  ( $B \rightarrow \bar{D} \tilde{D}_{1s}$ ), (c)  $\bar{B} \rightarrow \pi^- \tilde{D}_{s\bar{s}}, \pi^- \bar{D}$ , (d)  $\bar{B} \rightarrow \bar{D} \tilde{D}_{s\bar{s}}^0$ .

We give 5 types of production processes, showing the richness.

$B \rightarrow \bar{D}^{(*)} \tilde{D}_{0s}^+$  The standard  $\bar{b} \rightarrow c \bar{c} \bar{s}$  decay leads to  $B \rightarrow \bar{D} D_s^+$ , which is factorization dominant. As illustrated in Fig. 2(a), the  $J^+$  vector current can produce a scalar meson, which is not suppressed because of  $c$  and light quark mass imbalance. However, under factorization, it is precisely only the singly charged isosinglet state,  $\tilde{D}_{0s}^+$ , that can be produced. Applying the equation of motion which leads to

$$\begin{aligned} m_{a_0}^2 f_{a_0^-} &= i(m_d - m_u) \langle a_0^- | \bar{d} u | 0 \rangle, \\ m_{\tilde{D}_{0s}}^2 f_{\tilde{D}_{0s}} &= i(m_c - m_s) \langle \tilde{D}_{0s} | \bar{c} s | 0 \rangle, \end{aligned} \quad (10)$$

and assuming  $\langle \tilde{D}_{0s} | \bar{c} s | 0 \rangle \approx \langle a_0^- | \bar{d} u | 0 \rangle$ , it follows that  $f_{\tilde{D}_{0s}} \approx 67 \pm 13$  MeV for  $m(\tilde{D}_{0s}) \approx 2.32$  GeV and  $f_{a_0^\pm} = 1.1 \pm 0.2$  MeV obtained from finite-energy sum rules [16]. For  $f_{D_s} \sim 230$  MeV, this means that the production rate of  $B \rightarrow \bar{D} \tilde{D}_{0s}^+$  is smaller than that of  $B \rightarrow \bar{D} D_s^+$  by one order of magnitude. It is important to confirm the  $D_s^+(2320)$  state recoiling against a  $\bar{D}$  meson in  $B$  decay.

$B^+ \rightarrow D^{(*)-} \tilde{D}_{1s}^{++}$  ( $B \rightarrow \bar{D}^{(*)} \tilde{D}_{1s}$ ) To overcome the limitation of Fig. 2(a) to singly charged isosinglet state under factorization, we construct a process whereby the exotic doubly charged  $\tilde{D}_{1s}^{++}$  state can be produced. This is illustrated in Fig. 2(b), where the popping of a  $d\bar{d}$  pair between  $c\bar{c}$  allows  $B^+$  to decay to a  $D^{(*)-}$  plus the  $\tilde{D}_{1s}^{++}$ . The latter can

be searched for in  $D_s^+ \pi^+$ , or possibly  $D^+ K^+$  channels. It would be astonishing if a doubly charged resonance is found. Note that Fig. 2(b) provides a generic mechanism for  $B \rightarrow \bar{D} \tilde{D}_s$ , i.e., all four  $\tilde{D}_s$  states can be produced this way, with appropriate pairing with a  $\bar{D}$  meson. For example, the neutral state can be produced via  $B^0 \rightarrow \bar{D}^0 \tilde{D}_{1s}^0$ , which can be searched for via  $\tilde{D}_{1s}^0 \rightarrow D_s^+ \pi^-$ , or perhaps  $D^0 K^0$  if allowed.

$\bar{B} \rightarrow \pi^- \tilde{D}_{s\bar{s}}, \pi^- \bar{D}$  We illustrate in Fig. 2(c) a second type of factorized production process, via  $b \rightarrow c \bar{u} d$ . A  $\pi^-$  is emitted in standard way, but the  $b \rightarrow c$  current excites the effective popping of an  $s\bar{s}$  pair in the recoil system, and a  $\tilde{D}_{s\bar{s}}$  state can be formed, which decays to  $D_s^+ \bar{K}$  or perhaps  $D\eta$ . Likewise, but perhaps more difficult to disentangle experimentally, the  $\bar{D}$  state can be produced, which would decay to  $D\pi$ .

$\bar{B} \rightarrow \bar{D}^{(*)} \tilde{D}_{s\bar{s}}$  To see how the exotic  $\tilde{D}_{s\bar{s}}$  state can be produced, we reverse all quark directions in Fig. 2(a) and reshuffle the  $s$  quark to pair with the  $c$  quark from  $b \rightarrow c$  transition, as illustrated in Fig. 2(d). It is not clear whether Nature holds sufficient dynamics for this, but it is best to resort to data. Note that the  $\tilde{D}_{s\bar{s}}$  leads to “wrong” pairings of  $D^0 \bar{K}^0$  and  $D^+ K^-$  compared to usual  $B$  decay.

$\bar{B}^0 \rightarrow \bar{K} \tilde{D}_s, K^0 \tilde{D}_s^0$  Finally, we turn to nonfactorized processes that may also produce  $cq\bar{q}\bar{q}$  states. The process  $\bar{B}^0 \rightarrow K^- D_s^+$  has been observed by Belle [17] and BaBar [18] at a rate that cannot come from factorized amplitudes, but arise from either final state rescattering, or from annihilation diagrams. Either way, annihilation, exchange of constituents, and  $q\bar{q}$  popping can provide further avenues for 4-quark state search. For example, based on  $s\bar{u}c\bar{s}$  configuration already present in  $\bar{B}^0 \rightarrow K^- D_s^+$  final state, popping of  $d\bar{d}$  or  $u\bar{u}$  pairs can lead to  $\bar{B}^0 \rightarrow K^- \tilde{D}_{1s}^+, \bar{K}^0 \tilde{D}_{1s}^0$ , as well as the  $K^0 \tilde{D}_s^0$  final states. Thus, one not only should see the  $D_s(2320) \rightarrow D_s^+ \pi^0$  state recoiling against a single  $K^{(*)-}$  (with overlap of the narrow and the broad state), but perhaps also search for  $\bar{B}^0 \rightarrow K_S[D_s^+ \pi^-]$  ( $K_S[D^0 K^0]$ ) and  $\bar{B}^0 \rightarrow K_S[D^0 \bar{K}^0]$ ,  $K_S[D^+ \bar{K}^-]$ . Besides the distinct  $D^+ \bar{K}^-$  channel, for  $D^0 K_S$  one in principle can also use mass separation.

Our discussion has only been illustrative rather than exhaustive. The main point is that  $B$  decays may act as a “filter” through  $B$  reconstruction. In comparison, although the  $D_s(2320)$  state was discovered in charm fragmentation of  $e^+e^- \rightarrow c\bar{c}$ , to find broad resonances through such processes would be much more difficult.

## 5. Exotic charmonia and slow $J/\psi$ from $B$ decay?

It is natural to extend from  $cq\bar{q}\bar{q}$  to  $cq\bar{q}\bar{c}$  scalar states, which form an  $\mathbf{8} \oplus \mathbf{1}$ . Continuing our main assumption, the octet consists of an isotriplet and isosinglet composed of  $[nc\bar{c}\bar{n}]$ , plus two isodoublets  $[nc\bar{c}\bar{s}]$  and its charge conjugate. The heavy singlet has  $[sc\bar{c}\bar{s}]^0$  structure. If we extrapolate from the naive model of Eq. (1), we find

$$\begin{aligned} m_{nc\bar{c}\bar{n}} &\sim 3600 \text{ MeV} \lesssim m_{D\bar{D}}, \\ m_{nc\bar{c}\bar{s}} &\sim 3800 \text{ MeV} \lesssim m_{D_s\bar{D}}, \\ m_{sc\bar{c}\bar{s}} &\sim 4000 \text{ MeV} \lesssim m_{D_s\bar{D}_s}, \end{aligned} \quad (11)$$

although whether  $[sc\bar{c}\bar{s}]^0$  is still below  $D_s\bar{D}_s$  threshold is more dubious.

From Eq. (11) one can infer the dominant decay modes. If the isosinglet  $[nc\bar{c}\bar{n}]_0^0$  is below  $D\bar{D}$ , the dominant decay would be  $[nc\bar{c}\bar{n}]_0^0 \rightarrow \eta_c\eta$ , since it is clearly above the  $\eta_c\eta$  threshold. For the isotriplet,  $[nc\bar{c}\bar{n}]_1 \rightarrow \eta_c\pi$  should be the leading decay, but the  $[nc\bar{c}\bar{n}]_1 \rightarrow J/\psi\rho^* \rightarrow J/\psi\pi\pi$  decay, with  $\pi\pi$  peaking towards  $m_\rho$ , could be substantial. If the isodoublet  $[nc\bar{c}\bar{s}]$  is below  $D_s\bar{D}$  threshold, the leading decays may be  $\eta_c K$ , or  $J/\psi K\pi$  with  $m_{K\pi}$  peaked towards  $m_{K^*}$  (perhaps less prominent than  $\rho$  case because of smaller  $K^*$  width).

We are intrigued to stress that there may be some bearing for this already, in the observed “lump” for slow momentum  $J/\psi$ s below  $p_{J/\psi}^* \lesssim 1 \text{ GeV}$  observed in inclusive  $B$  decay. Such effect has been observed by all three experiments [19], and can only be of hadronic origin. The scenario of  $B \rightarrow K^{(*)} + [nc\bar{c}\bar{n}]_1 \rightarrow K + J/\psi(\pi\pi)_{\rho^*}$  and  $B \rightarrow (\pi, \rho) + [nc\bar{c}\bar{s}] \rightarrow K + J/\psi(K\pi)_{K^*}$  provide interesting possibilities whereby  $J/\psi$  is forced slow by  $m_{\pi\pi}$  ( $m_{K\pi}$ ) peaking towards  $\rho$  ( $K^*$ ) mass. But since in general the  $K^{(*)}\eta_c\eta$  or  $(\pi, \rho)\eta_c K$  modes should be dominant, one should search for these modes as crosschecks. Not only one has interest to understand what is behind the slow  $J/\psi$

bump in  $B$  decay, one may possibly uncover  $J/\psi\pi\pi$ ,  $\eta_c\eta$ ,  $\eta_c\pi$ , or  $J/\psi K\pi$ ,  $\eta_c K$  4-quark resonances.

Finally, if the  $[sc\bar{c}\bar{s}]^0$  configuration resonates, it may lead to  $B \rightarrow K\phi J/\psi$  (observed by CLEO [20]) and  $B \rightarrow K\eta^{(\prime)}\eta_c$ , which also should be studied.

Incidentally, we note that in principle  $c\bar{c}$  could annihilate via a single virtual gluon, i.e.,  $c\bar{c} \rightarrow g^* \rightarrow q\bar{q}$ . It would be interesting to see if the  $B \rightarrow K K_S K^- \pi^+$  decay, which Belle claimed [21] to uncover the  $\eta_c(2S)$  state in  $K_S K^- \pi^+$  decay, could contain some information on a possible  $[nc\bar{c}\bar{n}]$  state, as the  $\eta_c(2S)$  mass found at 3654 MeV seems on the high side (by  $\sim 100$  MeV compared to potential model expectations, but could be consistent with the  $[nc\bar{c}\bar{n}]$  states.

We should also stress that exotic  $0^+$  charmonia could also be searched for directly in charm fragmentation, e.g., in the recoil system of  $e^+e^- \rightarrow J/\psi + X$  at  $B$  Factory energies. It may in fact shed light on the rather mysterious  $e^+e^- \rightarrow cc\bar{c}$  production observed by Belle.

## 6. Discussion and conclusion

There is one potential problem for the 4-quark interpretation of  $D_s(2320)$  observed by BaBar: There is also hint [1] for a 2460 MeV state that decays to  $D_s^*\pi^0$ , i.e., in the  $D_s^+\pi^0\gamma$  final state. The existence of this state was not yet conclusive in the BaBar paper, but if it holds as another resonance, it cannot be of  $0^+$  quantum number. The naive guess would be  $1^+$ . If so, one interpretation of the  $D_s(2320)$  and “ $D_s(2460)$ ” pair would be the  $j = 1/2$   $s$ -spin doublet of  $0^+$  and  $1^+$ . The question then gets translated into why these states seem considerably lower in mass than expected. For instance, the paper by Di Pierro and Eichten [2] gives the masses at 2490 MeV and 2600 MeV, respectively, and one usually expects these states to be broad. If the  $0^+$  state moves below  $DK$  threshold, one ends up with the isospin violating  $D_s^+\pi^0$  decay as dominant mode. But for the  $1^+$  state, further mystery is why its rate is not dominated by  $D_s(2460) \rightarrow D_s^+\pi\pi$ , an allowed strong decay;  $D_s(2460) \rightarrow D_s^*\pi^0$  decay still would violate isospin. The width observed by BaBar for the 2460 MeV state is barely larger than resolution. We think it is far fetched at present to consider  $1^+$  states composed of  $cq\bar{q}\bar{q}$  (in principle one could also consider  $cg\bar{q}$  “hybrids”), and again

the relative narrowness would come into question. We look forward to clear establishment of the  $D_s^{*+}\pi^0$  state at 2460 MeV to clarify the situation.

In conclusion, starting from the observed narrow  $D_s(2320)$  state by BaBar, together with the possibility of an emerging light scalar nonet, we have explored the possible interpretation via  $cq\bar{q}\bar{q}$  4-quark states, which could naturally be below  $DK$  threshold. We give a naive picture of the states, their masses, and infer the corresponding decay modes. Only the  $D_s(2320)$  state, identified as the  $\bar{D}_{0s}^+$  isosinglet with  $[c(n\bar{n})_+\bar{s}]^+$  composition, decays dominantly by isospin violating decay and is narrow. The remaining triplet, two doublets, and a heavy singlet all decay hadronically, hence broad. The decay signatures are distinct. Particularly noteworthy are resonances in the doubly charged  $D_s^+\pi^+$  ( $D^+K^+$ ), and wrong pairing  $D^+K^-$  channels. We propose a host of  $B$  decays as possible “spectroscopes” to search for these exotic resonances, and give many explicit channels for further study. The hadronic width of these particles may hamper the analogous program for direct search in charm fragmentation. We extend the picture to include  $qc\bar{c}\bar{q}$  states, which may lead to exotic  $0^+$  charmonia resonances that could be behind the slow  $J/\psi$  excess in  $B$  decay, and may shed light on  $e^+e^- \rightarrow cc\bar{c}\bar{c}$  production. It is clear that only by establishing a clear spectroscopy of at least half the multiplets, can one start to put some faith in the  $cq\bar{q}\bar{q}$  (or  $qc\bar{c}\bar{q}$ ) 4-quark meson scenario.

### Note added

After this Letter was completed, we noticed the appearance of the related works by R.N. Cahn, J.D. Jackson, hep-ph/0305012, and T. Barnes, F.E. Close, H.J. Lipkin, hep-ph/0305025. Based on heavy quark effective theory and chiral perturbation theory, W.A. Bardeen, E.J. Eichten and C. Hill (hep-ph/0305049) have suggested that the newly observed  $D_s(2320)$  is the  $0^+ c\bar{s}$  state and that there is a  $1^+$  chiral partner with the same mass splitting with respect to the  $1^-$  state as that between the  $0^+$  and  $0^-$  states. Interestingly, this mass splitting was predicted a decade ago by M.A. Nowak, M. Rho and I. Zahed (Phys. Rev. D 48 (1993) 4370) to be of the same order as the light constituent quark mass. However, a renewed lattice calculation

presented by G.S. Bali (hep-ph/0305209) yields a larger mass than what is observed. Finally, it should be remarked that the existence of a new narrow resonance with a mass near 2.46 GeV has been observed by CLEO (D. Besson et al., hep-ex/0305100).

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