Heavy-Quark Symmetry Implies Stable Heavy Tetraquark Mesons $Q_i Q_j \bar{q}_k \bar{q}_l$

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For very heavy quarks $Q$, relations derived from heavy-quark symmetry predict the existence of novel narrow doubly heavy tetraquark states of the form $Q_i Q_j \bar{q}_k \bar{q}_l$ (subscripts label flavors), where $q$ designates a light quark. By evaluating finite-mass corrections, we predict that double-beauty states composed of $b b \bar{q}_k \bar{q}_l$, mixed beauty+charm states $b c \bar{q}_k \bar{q}_l$, and heavier $b b \bar{q}_k \bar{q}_l$ states will dissociate into pairs of heavy-light mesons. Observation of a new double-beauty state through its weak decays would establish the existence of tetraquarks and illuminate the role of heavy color-antitriplet diquarks as hadron constituents.

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Following the discovery of the charmonium-associated state $X(3872)$ by the BELLE collaboration [1], experiments have led a renaissance in hadron spectroscopy [2].

Many of the newly observed states invite identification with compositions less sparse than the traditional quark–antiquark meson and three-quark baryon schemes [3]. Tetraquark states composed of a heavy quark and antiquark plus a light quark and antiquark have attracted much attention. The observed candidates all fit the form $c \bar{c} q_k \bar{q}_l$, where the light quarks $q$ may be $u, d, o, s$. No such states are observed significantly below threshold for strong decays into two heavy-light meson states $c \bar{c} q + c \bar{c} q'$; all have strong decays to $c \bar{c}$ charmonium + light mesons.

In this Letter we examine the possibility of tetraquark configurations for which all strong decays are kinematically forbidden. We show that, in the heavy-quark limit, stable—hence exceedingly narrow—$Q_i Q_j \bar{q}_k \bar{q}_l$ mesons must exist. To apply this insight, we take into account corrections for finite heavy-quark masses to deduce which tetraquark states containing $b$ or $c$ quarks should be stable. The most promising example is a $J^{P} = 1^{+}$ isoscalar double-$b$ meson, $\Upsilon^{(bb)}$.

In the heavy-quark limit, the lowest-lying tetraquark configurations resemble the helium atom, a factorized system with separate dynamics for the compact heavy color-$3$ $Q_i Q_j$ “nucleus” and for the light quarks bound to the stationary color charge. (We recall that the one-gluon-exchange interaction is attractive for two quarks forming a color antitriplet, with half the strength of the attraction between a quark and antiquark bound in a color singlet.) At large $Q_i - Q_j$ separations, which become increasingly important as the heavy-quark masses decrease, the light $\bar{q}_k \bar{q}_l$ cloud screens the $Q_i Q_j$ interaction, so that the $Q_i Q_j \bar{q}_k \bar{q}_l$ complex may rearrange into a pair of heavy-light mesons [4]. For heavy quarks $Q_i Q_j$ bound in a color $3$ by an effective potential of the “Cornell” Coulomb+linear form at half strength for both components [5], the rms core radii are $(r^2)^{1/2} = 0.28$ fm (cc); 0.24 fm (bc); 0.19 fm (bb), all considerably smaller than the size of the associated tetraquark states. Hence the core-plus-light (anti)quarks idealization should be a reliable guide to the masses of ground-state tetraquarks containing charms and bottoms.

The ground state of the attractive $3$ $Q_i Q_j$ configuration may have total spin $S_{Q_i Q_j} = 1$ for identical quarks $(i = j)$ or for quarks of different flavors $(i \neq j)$ in a symmetric flavor configuration $\{Q_i Q_j\}$ or total spin $S_{Q_i Q_j} = 0$ for quarks of different flavors $(i \neq j)$ in an antisymmetric flavor configuration $[Q_i Q_j]$. To construct a color-singlet $Q_i Q_j \bar{q}_k \bar{q}_l$ state, the light $\bar{q}_k \bar{q}_l$ must be in a color-$3$. For the tetraquark ground state, both the heavy $Q_i Q_j$ and light $\bar{q}_k \bar{q}_l$ pairs must be in $(\ell = 0)$ s-waves. To satisfy the Pauli principle, the flavor-symmetric $\{\bar{q}_k \bar{q}_l\}$ state must have total (light-quark) spin $j_\ell = 1$, whereas the flavor-antisymmetric $[\bar{q}_k \bar{q}_l]$ must have $j_\ell = 0$.

Stability in the heavy-quark limit. For very heavy quarks, a hadron mass receives negligible contributions from the motion of the heavy quarks and spin interactions. Accordingly, the following relations hold among the masses of heavy-light and doubly-heavy-light mesons and baryons [6]:

\[
\begin{align*}
  m(\{Q_i Q_j\}\bar{q}_k \bar{q}_l) - m(\{Q_i Q_j\} q_y) &= m(Q_x \{q_y q_l\}) - m(Q_x \bar{q}_y) \\
  m(\{Q_i Q_j\}\bar{q}_k \bar{q}_l) - m(\{Q_i Q_j\} q_y) &= m(Q_x \{q_y q_l\}) - m(Q_x \bar{q}_y) \\
  m([Q_i Q_j]\bar{q}_k \bar{q}_l) - m([Q_i Q_j] q_y) &= m(Q_x \{q_y q_l\}) - m(Q_x \bar{q}_y) \\
  m([Q_i Q_j]\bar{q}_k \bar{q}_l) - m([Q_i Q_j] q_y) &= m(Q_x \{q_y q_l\}) - m(Q_x \bar{q}_y) \\
  m(\{Q_i Q_j\}\bar{q}_k \bar{q}_l) - m(\{Q_i Q_j\} q_y) &= m(Q_x \{q_y q_l\}) - m(Q_x \bar{q}_y) .
\end{align*}
\]
(In the limit, a heavy core is a heavy core.)

It is easy to see that the dissociation of $Q_i Q_j q_k q_l$ into two heavy-light mesons is kinematically forbidden, for sufficiently heavy quarks. The $Q$ value for the decay is

$$Q \equiv m(Q_i Q_j q_k q_l) - [m(Q_i q_k) + m(Q_j q_l)] = 
\Delta(q_k, q_l) - \frac{1}{2}(\frac{3}{2} \alpha_s)^2 [1 + O(\alpha^2)] M + O(1/M),$$ (2)

where $\Delta(q_k, q_l)$, the contribution due to light dynamics, becomes independent of the heavy-quark masses, $M \equiv (1/m_{q_k} + 1/m_{q_l})^{-1}$ is the reduced mass of $q_i$ and $q_j$, and $\alpha_s$ is the strong coupling. The velocity-dependent hyperfine corrections, here negligible, are calculable in the nonrelativistic QCD formalism \[7\]. For large enough values of $M$, the middle term dominates, so the tetraquark is stable against decay into two heavy-light mesons.

The other possible decay channel is to a doubly heavy baryon and a light antibaryon,

$$(Q_i Q_j q_k q_l) \to (Q_i Q_j q_m) + (\bar{q}_k q_l q_m).$$ (3)

By Eq. 1 we have

$$m(Q_i Q_j q_k q_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x q_m) .$$ (4)

In the heavy-quark regime, the flavored-baryon–flavored-meson mass difference on the right-hand side of Eq. 1 has the generic form $\Delta_0 + \Delta_1/M Q_i Q_j$. Using the observed mass differences, $m(\Lambda_c) - m(D) = 416.87$ MeV and $m(\Lambda_b) - m(B) = 340.26$ MeV, and choosing effective quark masses $m_c \equiv m(J/\psi)/2 = 1.55$ GeV, $m_b \equiv m(\Upsilon)/2 = 4.73$ GeV, we find $\Delta_1 = 176.6$ MeV$^2$ and $\Delta_0 = 303$ MeV, hence the mass difference in the heavy-quark limit is 303 MeV. All of these mass differences are smaller than the mass of the lightest antibaryon, $m(\bar{p}) = 938.27$ MeV, so we conclude that no decay to a doubly heavy baryon and a light antibaryon is kinematically allowed. This completes the demonstration that, in the heavy-quark limit, stable $Q_i Q_j q_k q_l$ mesons must exist.

**Beyond the heavy-quark limit.** To ascertain whether stable tetraquark mesons might be observed, we must estimate masses of the candidate configurations. Numerous model calculations exist in the literature \[8\] but not informative to make estimates in the spirit of heavy-quark symmetry.

The leading-order corrections for finite heavy-quark mass correspond to hyperfine spin-dependent terms and a kinetic energy shift that depends only on the light degrees of freedom,

$$\delta m = S \cdot \vec{J} \cdot \vec{j} \cdot \vec{J} + \frac{\mathcal{K}}{2M},$$ (5)

where $\mathcal{M} = m_{Q_i}$ or $m_{Q_i} + m_{Q_j}$ denotes the mass of the heavy-quark core for hadrons containing one or two heavy quarks and the coefficients $S$ and $\mathcal{K}$ are to be determined from experimental data summarized in Table 1. The spin splittings lead directly to the coefficients $S$ tabulated in the last column. The pattern of the spin coefficients is entirely consistent with the expectations of heavy-quark symmetry.

The kinetic energy shift due to light quarks will be different in $Q \bar{q}$ mesons and $Q q q$ baryons. By comparing the centroid (or center-of-gravity, c.g.) masses for the charm and bottom systems we can extract the difference of the kinetic-energy coefficients $\mathcal{K}$ for states that contain one or two light quarks, viz. $\delta \mathcal{K} \equiv \mathcal{K}_{(ud)} - \mathcal{K}_{(d)}$. For example,

$$\{m[(cad)\bar{a}] - m[(d\bar{a})]\} - \{m[(bud)\bar{a}] - m[(b\bar{a})]\}$$

$$= \delta \mathcal{K} \left( \frac{1}{2m_c} - \frac{1}{2m_b} \right) = 5.11 \text{ MeV},$$ (6)

from which we extract $\delta \mathcal{K} = 0.0235 \text{ GeV}^2$. The resulting mass shifts are

$$m[(cc)\bar{d}] - m[(cc)d] : \frac{\delta \mathcal{K}}{4m_c} = 2.80 \text{ MeV}$$ (7)

$$m[(bc)\bar{d}] - m[(bc)d] : \frac{\delta \mathcal{K}}{2(m_c + m_b)} = 1.87 \text{ MeV}$$

$$m[(bb)\bar{d}] - m[(bb)d] : \frac{\delta \mathcal{K}}{4m_b} = 1.24 \text{ MeV}$$

These values are small—only slightly larger than the isospin breaking effects that we neglect as too small to affect the question of stability \[12\].

Combining the heavy-quark-symmetry relations of Eq. 1 with the leading-order corrections we obtain the masses of ground-state $Q_i Q_j q_k q_l$ tetraquarks summarized in Table 11 \[13\]. As inputs for the doubly heavy baryons not yet experimentally measured, we use the model calculations of Karliner and Rosner \[14\].

**Narrow Tetraquark States.** As we explained in the discussion surrounding Eq. 1 strong decays of $Q_i Q_j q_k q_l$ tetraquarks to a doubly heavy baryon and a light antibaryon are kinematically forbidden for all the ground states. Strong decay to a pair of heavy-light mesons will occur if the tetraquark state lies above threshold. For $J^P = 0^+$ or $2^+$, a $Q_i Q_j q_k q_l$ meson might decay to a pair of heavy-light pseudoscalar mesons while for $J^P = 1^+$ the allowed decay channel would be a pseudoscalar plus a vector meson. According to our mass estimates, the only tetraquark mesons below threshold are the axial vector $\{bb\} \bar{u} \bar{d}$ meson, $\tau_{(bb)}^{(\bar{u} \bar{d})}$, that is bound by 121 MeV and the axial vector $\{bb\} \bar{i} \bar{s}$ and $\{bb\} \bar{d} \bar{s}$ mesons bound by 48 MeV. We expect all the other $Q_i Q_j q_k q_l$ tetraquarks to lie at least 78 MeV above the corresponding thresholds for strong decay \[10\]. Promising final states include $\tau_{(bb)}^{(\bar{u} \bar{d})} \to \Xi_{bc}^0 \bar{v}, B^- D^+ \pi^-$, and $B^- D^+ \ell^- \nu$ (which establishes a weak decay), $\tau_{(bb)}^{(\bar{u} \bar{s})} \to \Xi_{bc}^0 \bar{i}^-$, $\tau_{(bb)}^{(\bar{b} \bar{d})} \to \Xi_{bc}^0 (A, \Sigma^0)$, and so on.
As others have noted [8, 17], unstable doubly heavy tetraquarks might be reconstructed as resonances in the "wrong-sign" combinations of $DD, DB,$ and $BB$. The doubly charged $\Upsilon_{bc}^{(+)} \rightarrow D^+ D^+$, etc. would stand out as prima facie evidence for a non-$q\bar{q}$ level.

While the production of $Q_j Q_j \bar{q} \bar{q}$ mesons is undoubtedly a rare event, we draw some encouragement for near-term searches from the large yield of $B_c$ mesons recorded in the LHCb experiment [18], and the not inconsiderable rate of Double-$\Upsilon$ production observed in 8-TeV $p p$ collisions by the CMS experiment, $\sigma(pp \rightarrow \Upsilon \Upsilon +$ anything$) = 68 \pm 15$ pb [19]. The ultimate search instrument might be a future electron–positron Tera-$Z$ factory, for which the branching fractions [19] $Z \rightarrow b \bar{b} = 15.12 \pm 0.05\%$ and

| State $^a$ | $j^p$ | $m(Q_j Q_j \bar{q} \bar{q})$, (c.g.) | HQS relation | $m(Q_j Q_j \bar{q} \bar{q})$ | Decay Channel | $Q$, [MeV] |
|---|---|---|---|---|---|---|
| $\{cc\} \{\bar{u} \bar{d}\}$ | 1$^+$ | 0 | $366^{+30}_{-21}$ | $m(\{cc\}u) + 315$ | $D^+ D^{*0}$ | 3876 | 102 |
| $\{cc\} \{\bar{q} \bar{q}\}$ | 1$^+$ | 0 | $376^{+30}_{-21}$ | $m(\{cc\}s) + 392$ | $D^+ D^{*+}$ | 3977 | 179 |
| $\{bc\} \{\bar{u} \bar{d}\}$ | 0$^+$ | 0 | 6914 | $m(\{bc\}u) + 315$ | $B^- D^- + B^0 D^+$ | 7146 | 83 |
| $\{bc\} \{\bar{q} \bar{q}\}$ | 1$^+$ | 1 | 6914 | $m(\{bc\}s) + 392$ | $B_s D$ | 7236 | 170 |
| $\{bc\} \{\bar{u} \bar{d}\}$ | 0$^+$ | 0 | 7010$^{+30}_{-21}$ | $m(\{bc\}u) + 526$ | $B_s D / (B^0 D^*)$ | 7190/7290 | 249 |
| $\{bc\} \{\bar{q} \bar{q}\}$ | 1$^+$ | 1 | 6957 | $m(\{bc\}s) + 392$ | $B_s D / (B^0 D^*)$ | 7190/7290 | 82 |
| $\{cc\} \{\bar{q} \bar{q}\}$ | 0$^+$, 1$^+$, 2$^+$ | 1 | 6957 | $m(\{cc\}u) + 526$ | $B_s D$ | 7236 | 170 |
| $\{cc\} \{\bar{q} \bar{q}\}$ | 1$^+$ | 1 | 10176 | $m(\{bb\}u) + 306$ | $B^- \bar{B}^{*0}$ | 10 603 | –121 |
| $\{bb\} \{\bar{q} \bar{q}\}$ | 1$^+$ | 0 | 10 252$^{+20}_{-13}$ | $m(\{bb\}s) + 391$ | $BB_s^* / B_s B^*$ | 10 695/10 691 | –48 |
| $\{bb\} \{\bar{q} \bar{q}\}$ | 1$^+$, 2$^+$, 1$^+$ | 1 | 10 176 | $m(\{bb\}u) + 512$ | $10 674, 10 681, 10 695$ | $B^- B^0, B^- B^{*0}$ | 10 559, 10 603 | 115, 78, 136 |

$^a$ Subscripts denote flavor-SU(3) representations for heavy baryons.

$^b$ From the LHCb observation, Ref. [10].

$^c$ Inferred from the lattice QCD calculation of Ref. [11].
\[ Z \to bbb \bar{b} = (3.6 \pm 1.3) \times 10^{-4} \text{ offer hope of many events containing multiple heavy quarks.} \]

**Concluding remarks.** We have shown that, in the heavy-quark limit, stable \( Q_i Q_j q_i q_j \) tetraquarks must exist. Our estimates of tetraquark masses lead us to expect that strong decays of the \( J^P = 1^+ \) \( \{ bb \} \bar{u}d \), \( \{ bb \} \bar{u}s \), and \( \{ bb \} \bar{d}s \) states are kinematically forbidden, so that these states should be exceedingly narrow, decaying only through the charged-current weak interaction. Observation of any of these states would signal the existence of a new form of stable matter, in which the doubly heavy color-3 \( Q_i Q_j \) diquark is a basic building block. The unstable \( Q_i Q_j q_i q_j \) tetraquarks—particularly those with small \( Q \) values—may be observable as resonances decaying into pairs of heavy-light mesons, if they are not too broad to stand out above backgrounds.

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**Note added.**—We recently learned of interesting calculations of tetraquark masses that also highlight the likelihood of a stable doubly heavy tetraquark \[20\].

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Communication with decay channels tends to push the bound-state levels deeper. Open channels would induce mixing between the color-\(\bar{3}-\bar{3}\)-core–\(\bar{3}\)-light quark configuration and meson–meson configurations.

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Note that if we took the SELEX value for the \(\Xi_{cc}^+\) mass, 3519 MeV, rather than the LHCb \(\Xi_{cc}^{++}\) mass of Ref. 10, M. Mattson et al. (SELEX Collaboration), “First observation of the doubly charmed baryon \(\Xi_{cc}^+\),” Phys. Rev. Lett. 89, 112001 (2002), arXiv:hep-ex/0208014 [hep-ex] we would find \(m(\{cc\}[\bar{u}\bar{d}]) = 3876\) MeV, coincident with the 3876 MeV threshold for dissociation into a heavy-light pseudoscalar and heavy-light vector. Signatures for weak decay would include \(D^+ K^- \ell^+ \nu\) and \(\Xi_{cc}^\pm \bar{n}\).

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