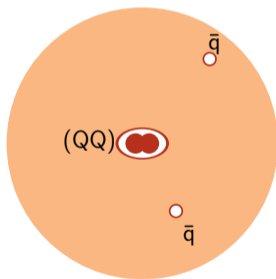


# Stable Tetraquarks

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Moriond QCD · La Thuile · 20 March 2018

Estia Eichten & CQ, PRL **119**, 202002 (2017) / arXiv:1707.09575

Heavy-quark symmetry implies stable heavy tetraquark mesons  $Q_i Q_j \bar{q}_k \bar{q}_l$

*In the limit of very heavy quarks  $Q$ , novel narrow doubly heavy tetraquark states (DHTQ) must exist.*

*HQS relates DHTQ mass to masses of a doubly heavy baryon, heavy-light baryon, and heavy-light meson.*

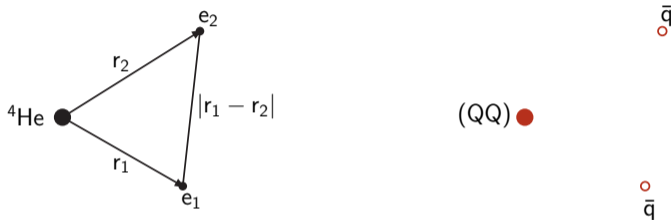
*The lightest double-beauty states composed of  $bb\bar{u}\bar{d}$ ,  $bb\bar{u}\bar{s}$ , and  $bb\bar{d}\bar{s}$  will likely be stable against strong decays.*

*Heavier  $bb\bar{q}_k\bar{q}_l$  states,  $cc\bar{q}_k\bar{q}_l$  states, and mixed  $bc\bar{q}_k\bar{q}_l$  states, will likely dissociate into pairs of heavy-light mesons. Some might be seen as “double-flavor” resonances near threshold.*

*Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color- $\bar{\mathbf{3}}$  diquarks as hadron constituents.*

# When tetraquarks resemble the helium atom ...

Factorized system: separate dynamics for compact “nucleus,” light quarks



(Attractive, **repulsive**) one-gluon exchange for  $(QQ)$  in color- $(\bar{3}, 6)$   
 $\bar{3}$  half strength of  $Q\bar{Q}$  attraction in color-**1**  
also for string tension [Nakamura & Saito]

In heavy limit, idealize a stationary, structureless (color) charge

# Stability in the heavy-quark limit

1) *Dissociation into two heavy-light mesons is kinematically forbidden.*

$$\mathcal{Q} \equiv m(Q_i Q_j \bar{q}_k \bar{q}_l) - [m(Q_i \bar{q}_k) + m(Q_j \bar{q}_l)] =$$
$$\underbrace{\Delta(q_k, q_l)}_{\text{light d.o.f.}} - \frac{1}{2} \left( \frac{2}{3} \alpha_s \right)^2 [1 + O(v^2)] \bar{M} + O(1/\bar{M}),$$

$\bar{M} \equiv (1/m_{Q_i} + 1/m_{Q_j})^{-1}$ : reduced mass of  $Q_i$  and  $Q_j$

$\Delta(q_k, q_l) \xrightarrow{\bar{M} \rightarrow \infty}$  independent of heavy-quark masses

For large enough  $\bar{M}$ ,  $QQ$  Coulomb binding dominates,  $\mathcal{Q} < 0$

## Stability in the heavy-quark limit

2) *Decay to doubly heavy baryon and light antibaryon?*

$$(Q_i Q_j \bar{q}_k \bar{q}_l) \rightarrow (Q_i Q_j q_m) + (\bar{q}_k \bar{q}_l \bar{q}_m)$$

For very heavy quarks, negligible contributions from  $Q$  motion and spin interactions, so (spin configurations matter)

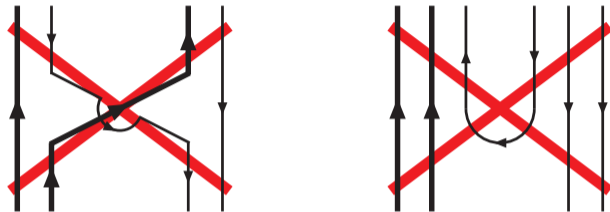
$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

RHS has generic form  $\Delta_0 + \Delta_1/M_{Q_x}$

With  $m(\Lambda_c) - m(D) = 416.87$  MeV and  $m(\Lambda_b) - m(B) = 340.26$  MeV, we estimate  $\Delta_0 \approx 330$  MeV (asymptotic mass difference).

$All < m(\bar{p}) = 938 \text{ MeV}$

# No open strong decay channels in the heavy-quark limit!

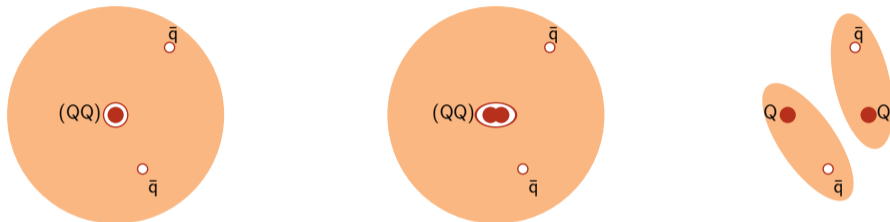


As  $\bar{M} \rightarrow \infty$ , stable  $Q_i Q_j \bar{q}_k \bar{q}_l$  mesons must exist

Implications for the real world?

# Does a tiny quasistatic diquark core make sense in our world?

At large  $Q_i - Q_j$  separations,  $\bar{q}_k \bar{q}_l$  cloud screens  $Q_i Q_j$  interaction



$\rightsquigarrow$  rearrangement into heavy–light mesons

In a half-strength Cornell potential, rms core radii are small on tetraquark scale:  $\langle r^2 \rangle^{1/2} = 0.28 \text{ fm } (cc); 0.24 \text{ fm } (bc); 0.19 \text{ fm } (bb)$ . (lattice, too)

$\therefore$  core-plus-light (anti)quarks idealization should be reliable.

# Mass estimates (beyond the heavy-quark limit ...)

Use heavy-quark-symmetry relations,

$$m(\{Q_i Q_j\}\{\bar{q}_k \bar{q}_l\}) - m(\{Q_i Q_j\}q_y) = m(Q_x\{q_k q_l\}) - m(Q_x \bar{q}_y)$$

$$m(\{Q_i Q_j\}[\bar{q}_k \bar{q}_l]) - m(\{Q_i Q_j\}q_y) = m(Q_x[q_k q_l]) - m(Q_x \bar{q}_y)$$

$$m([Q_i Q_j]\{\bar{q}_k \bar{q}_l\}) - m([Q_i Q_j]q_y) = m(Q_x\{q_k q_l\}) - m(Q_x \bar{q}_y)$$

$$m([Q_i Q_j][\bar{q}_k \bar{q}_l]) - m([Q_i Q_j]q_y) = m(Q_x[q_k q_l]) - m(Q_x \bar{q}_y) .$$

$$+ \text{finite-mass corrections, } \delta m = \mathcal{S} \frac{\vec{S} \cdot \vec{j}_\ell}{2\mathcal{M}} + \frac{\mathcal{K}}{2\mathcal{M}}$$

(hyperfine + light d.o.f.)

to estimate  $Q_i Q_j \bar{q}_k \bar{q}_l$  masses



# Kinetic-energy shift differs in $Q\bar{q}$ mesons and $Qqq$ baryons . . .

Consider  $\delta\mathcal{K} \equiv \mathcal{K}_{(ud)} - \mathcal{K}_d$ :

$$\begin{aligned} & [m((cud)_{\bar{3}}) - m(c\bar{d})] - [m((bud)_{\bar{3}}) - m(b\bar{d})] \\ &= \delta\mathcal{K} \left( \frac{1}{2m_c} - \frac{1}{2m_b} \right) = 5.11 \text{ MeV} \end{aligned}$$

$$\rightsquigarrow \delta\mathcal{K} = 0.0235 \text{ GeV}^2$$

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

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

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

Small! (only slightly larger than isospin-breaking effects we neglect)

# Estimating ground-state tetraquark masses

RHS of

$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

is determined from data

One doubly heavy baryon observed,  $\Xi_{cc}$ ; others from model calculations\*

$$\text{LHCb: } M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78 \text{ MeV}$$

\*We adopt Karliner & Rosner, *PRD* **90**, 094007 (2014)

Strong decays  $(Q_i Q_j \bar{q}_k \bar{q}_l) \not\rightarrow (Q_i Q_j q_m) + (\bar{q}_k \bar{q}_l \bar{q}_m) \forall$  ground states

Must consider decays to pairs of heavy–light mesons case-by-case

# Expectations for ground-state tetraquark masses, in MeV

State	$J^P$	$m(Q_i Q_j \bar{q}_k \bar{q}_l)$	Decay Channel	$Q$ [MeV]
$\{cc\}[\bar{u}d]$	$1^+$	3978	$D^+ D^{*0}$ 3876	102
$\{cc\}[\bar{q}_k \bar{s}]$	$1^+$	4156	$D^+ D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	$D^+ D^0, D^+ D^{*0}$ 3734, 3876	412, 292, 476
$[bc][\bar{u}d]$	$0^+$	7229	$B^- D^+ / B^0 D^0$ 7146	83
$[bc][\bar{q}_k \bar{s}]$	$0^+$	7406	$B_s D$ 7236	170
$[bc]\{\bar{q}_k \bar{q}_l\}$	$1^+$	7439	$B^* D / B D^*$ 7190/7290	249
$\{bc\}[\bar{u}d]$	$1^+$	7272	$B^* D / B D^*$ 7190/7290	82
$\{bc\}[\bar{q}_k \bar{s}]$	$1^+$	7445	$D B_s^*$ 7282	163
$\{bc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	7461, 7472, 7493	$B D / B^* D$ 7146/7190	317, 282, 349
$\{bb\}[\bar{u}d]$	$1^+$	10482	$B^- \bar{B}^{*0}$ 10603	-121
$\{bb\}[\bar{q}_k \bar{s}]$	$1^+$	10643	$\bar{B} \bar{B}_s^* / \bar{B}_s \bar{B}^*$ 10695/10691	-48
$\{bb\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	10674, 10681, 10695	$B^- B^0, B^- B^{*0}$ 10559, 10603	115, 78, 136

Cf. M. Karliner & J. L. Rosner model, Phys. Rev. Lett. **119**, 202001 (2017) [arXiv:1707.07666].  
 Estimate deeper binding, so additional  $bc$  and  $cc$  candidates.

Lattice studies also suggest stable double-beauty tetraquarks.

## Real-world candidates for stable tetraquarks

$J^P = 1^+ \{bb\}[\bar{u}\bar{d}]$  meson, bound by 121 MeV

(77 MeV below  $B^- \bar{B}^0 \gamma$ )

$\mathcal{T}_{[\bar{u}\bar{d}]}^{\{bb\}}(10482)^- \rightarrow \Xi_{bc}^0 \bar{p}, B^- D^+ \pi^-,$  and  $\underbrace{B^- D^+ \ell^- \bar{\nu}}$   
manifestly weak!

$J^P = 1^+ \{bb\}[\bar{u}\bar{s}]$  and  $\{bb\}[\bar{d}\bar{s}]$  mesons, bound by 48 MeV

(3 MeV below  $BB_s \gamma$ )

$\mathcal{T}_{[\bar{u}\bar{s}]}^{\{bb\}}(10643)^- \rightarrow \Xi_{bc}^0 \bar{\Sigma}^-$        $\mathcal{T}_{[\bar{d}\bar{s}]}^{\{bb\}}(10643)^0 \rightarrow \Xi_{bc}^0 (\bar{\Lambda}, \bar{\Sigma}^0)$

SELEX  $M(\Xi_{cc}^+) = 3519$  MeV  $\rightsquigarrow m(\{cc\}[\bar{u}\bar{d}]) = 3876$  MeV, at threshold for dissociation into a heavy-light pseudoscalar and heavy-light vector. Signatures for weak decay would include  $D^+ K^- \ell^+ \nu$  and  $\Xi_c^+ \bar{n}$ . ( $D^0 D^+ \gamma$  at 3734 MeV)

# Unstable doubly heavy tetraquarks

Resonances in “wrong-sign” (double flavor) combinations  $DD, DB, BB$ ?

$$\mathcal{T}_{[d\bar{s}]}^{\{cc\}++} \rightarrow D^+ D_s^+ : \textit{prima facie} \text{ evidence for a non-}q\bar{q} \text{ level}$$

(New kind of resonance: no attractive force at the meson–meson level.)

# Production of stable tetraquarks?

Undoubtedly rare! We offer no calculation, but note

- Large yield of  $B_c$  in LHCb:  $8995 \pm 103 B_c \rightarrow J/\psi \mu \nu_\mu X$  candidates in  $2 \text{ fb}^{-1}$   $pp$  collisions at 8 TeV
- CMS observation of double- $\Upsilon$  production in 8-TeV  $pp$  collisions:  
 $\sigma(pp \rightarrow \Upsilon\Upsilon + \text{anything}) = 68 \pm 15 \text{ pb}$

Ultimate search instrument? Future  $e^+e^-$  Tera-Z factory

Branching fractions  $Z \rightarrow b\bar{b} = 15.12 \pm 0.05\%$ ,  $b\bar{b}b\bar{b} = (3.6 \pm 1.3) \times 10^{-4}$

$\rightsquigarrow$  many events containing multiple heavy quarks

## Homework for experiment

Look for double-flavor resonances near threshold.

Discover and determine masses of doubly-heavy baryons.

*needed to implement HQS calculation of tetraquark masses*  
*intrinsic interest in these states: comparison with heavy—light mesons,*  
*possible core excitations*

Resolve  $\Xi_{cc}$  uncertainty (SELEX/LHCb)

Find stable tetraquarks through weak decays. Lifetime:  $\sim 1/3$  ps ??

## Homework for theory

Develop expectations for production.

Refine lifetime estimates for stable states.

Understand how color configurations evolve with  $QQ$  masses.

Investigate stability of other body plans in the heavy-quark limit.



## Other $Q_i Q_j \bar{q}_k \bar{q}_l$ configurations

All quarks heavy, one-gluon exchange prevails: No stable  $QQ\bar{Q}\bar{Q}$  (equal-mass) tetraquarks in very-heavy-quark limit. Support for binding of  $bb\bar{q}\bar{q}$ . Study  $N_c$  dependence.

A. Czarnecki, B. Leng, M. B. Voloshin, “Stability of tetrons,” arXiv:1708.04594.

Lattice–NRQCD study of  $bb\bar{b}\bar{b}$ : No tetraquark with mass below  $\eta_b\eta_b$ ,  $\Upsilon\Upsilon$  thresholds in  $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$  channels.

C. Hughes, E. Eichten, C. T. H. Davies, “The Search for Beauty-fully Bound Tetraquarks Using Lattice Non-Relativistic QCD,” arXiv:1710.03236.

Heavy-quark symmetry implies stable heavy tetraquark mesons  $Q_i Q_j \bar{q}_k \bar{q}_l$

*In the limit of very heavy quarks  $Q$ , novel narrow doubly heavy tetraquark states must exist.*

*Mass estimates lead us to expect that the  $J^P = 1^+$   $\{bb\}[\bar{u}\bar{d}]$ ,  $\{bb\}[\bar{u}\bar{s}]$ , and  $\{bb\}[\bar{d}\bar{s}]$  states should be exceedingly narrow, decaying only through the charged-current weak interaction*

*Observation would herald a new form of stable matter, in which the doubly heavy color- $\bar{\mathbf{3}}$   $Q_i Q_j$  diquark is a basic building block.*

*Unstable  $Q_i Q_j \bar{q}_k \bar{q}_l$  tetraquarks with small  $Q$ -values may be observable as resonant pairs of heavy-light mesons*