Stable Tetraquarks

Chris Quigg

Fermilab

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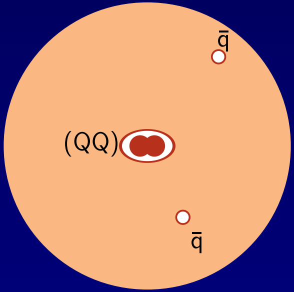

Estia Eichten & CQ, PRL **119**, 202002 (2017) / arXiv:1707.09575

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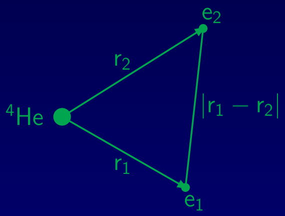
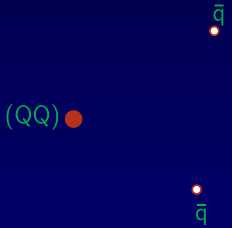
Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color-$\bar{\mathbf{3}}$ diquarks as hadron constituents.

When tetraquarks resemble the helium atom . . .

Factorized system: separate dynamics for compact "nucleus," light quarks





(Attractive, repulsive) one-gluon exchange for (QQ) in color-$(\bar{\mathbf{3}}, \mathbf{6})$

$\bar{\mathbf{3}}$ *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.*

$$\mathcal{Q} \equiv m(Q_i Q_j \bar{q}_k \bar{q}_l) - [m(Q_i \bar{q}_k) + m(Q_j \bar{q}_l)] =$$

$$\underbrace{\Delta(q_k, q_l)}_{\text{light d.o.f.}} - \tfrac{1}{2}\left(\tfrac{2}{3}\alpha_s\right)^2 [1 + O(v^2)]\overline{M} + O(1/\overline{M}) \,,$$

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

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

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

Stability in the heavy-quark limit

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

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

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Core $Q_i Q_j$ is color-$\bar{\mathbf{3}}$, same as $\bar{Q}_x$. Up to contributions from Q motion and spin interactions,

$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(\bar{Q}_x \bar{q}_k \bar{q}_l) - m(\bar{Q}_x q_m)$$

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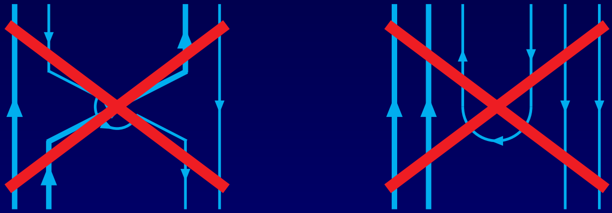
(spin configurations matter) RHS has generic form $\Delta_0 + \Delta_1 / M_{Q_x}$

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

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

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



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

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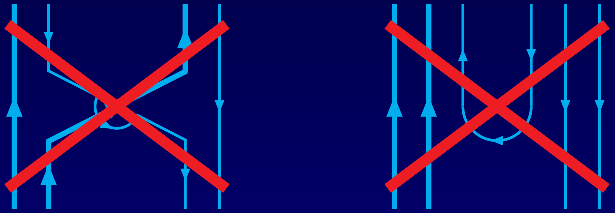

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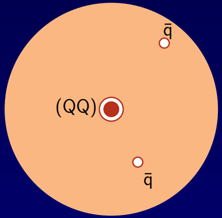
Implications for the real world?

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



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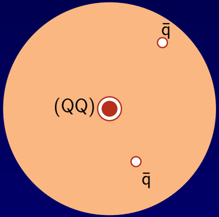

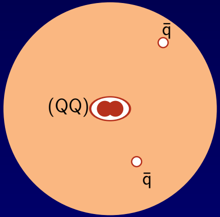

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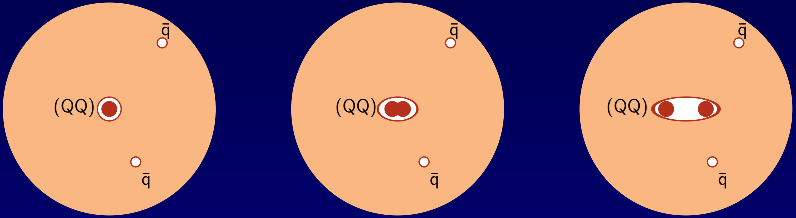

Growing separation alters $\bar{\mathbf{3}}$, $\mathbf{6}$ mix

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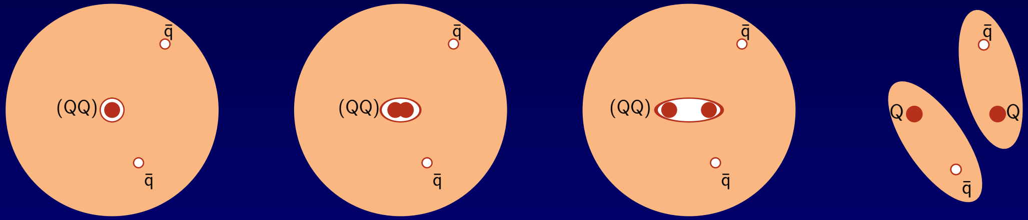

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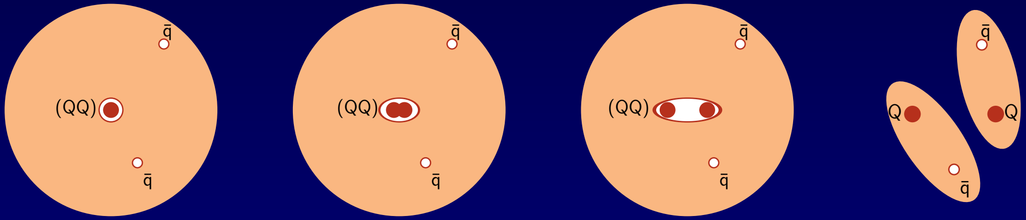

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In a half-strength Cornell potential, rms core radii are small on tetraquark scale: $\langle r^2 \rangle^{1/2} = 0.19$ fm (bb); 0.24 fm (bc); 0.28 fm (cc);. (lattice, too)

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

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

Use heavy-quark-symmetry relations,

$$\begin{aligned}
m(\{Q_iQ_j\}\{\bar{q}_k\bar{q}_l\}) - m(\{Q_iQ_j\}q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m(\{Q_iQ_j\}[\bar{q}_k\bar{q}_l]) - m(\{Q_iQ_j\}q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j]\{\bar{q}_k\bar{q}_l\}) - m([Q_iQ_j]q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j][\bar{q}_k\bar{q}_l]) - m([Q_iQ_j]q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y) \,.
\end{aligned}$$

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

(hyperfine + light d.o.f.)

to estimate $Q_iQ_j\bar{q}_k\bar{q}_l$ masses

Masses, etc., of ground-state hadrons containing heavy quarks

State	j_ℓ	Mass $(j_\ell + \frac{1}{2})$	Mass $(j_\ell - \frac{1}{2})$	Centroid	Spin Splitting	$\mathcal{S}$ [GeV^2]
$D^{(*)}\ (c\bar{d})$	$\frac{1}{2}$	2010.26	1869.59	1975.09	140.7	0.436
$D_s^{(*)}\ (c\bar{s})$	$\frac{1}{2}$	2112.1	1968.28	2076.15	143.8	0.446
$\Lambda_c\ (cud)_{\bar{\mathbf{3}}}$	0	2286.46	–	–		–
$\Sigma_c\ (cud)_{\mathbf{6}}$	1	2518.41	2453.97	2496.93	64.44	0.132
$\Xi_c\ (cus)_{\bar{\mathbf{3}}}$	0	2467.87	–	–		–
$\Xi'_c\ (cus)_{\mathbf{6}}$	1	2645.53	2577.4	2622.82	68.13	0.141
$\Omega_c\ (css)_{\mathbf{6}}$	1	2765.9	2695.2	2742.33	70.7	0.146
$\Xi_{cc}\ (ccu)_{\bar{\mathbf{3}}}$	0	3621.40	–		–	
$B^{(*)}\ (b\bar{d})$	$\frac{1}{2}$	5324.65	5279.32	5313.32	45.33	0.427
$B_s^{(*)}\ (b\bar{s})$	$\frac{1}{2}$	5415.4	5366.89	5403.3	48.5	0.459
$\Lambda_b\ (bud)_{\bar{\mathbf{3}}}$	0	5619.58	–		–	
$\Sigma_b\ (bud)_{\mathbf{6}}$	1	5832.1	5811.3	5825.2	20.8	0.131
$\Xi_b\ (bds)_{\bar{\mathbf{3}}}$	0	5794.5	–		–	
$\Xi'_b\ (bds)_{\mathbf{6}}$	1	5955.33	5935.02	5948.56	20.31	0.128
$\Omega_b\ (bss)_{\mathbf{6}}$	1		6046.1			
$B_c\ (b\bar{c})$	$\frac{1}{2}$	*6329*	6274.9	*6315.4*	*54*	*0.340*

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

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

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

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

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

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

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

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

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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

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One doubly heavy baryon observed, Ξ_{cc}; others from model calculations*

LHC*b*: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV

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Strong decays $(Q_iQ_j\bar{q}_k\bar{q}_l) \not\to (Q_iQ_jq_m) + (\bar{q}_k\bar{q}_l\bar{q}_m)$ $\forall$ 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	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	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
$[bc][\bar{u}\bar{d}]$	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
$\{bc\}[\bar{u}\bar{d}]$	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	$BD / B^* D$ 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	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

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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.

Real-world candidates for stable tetraquarks

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

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

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

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

(3 MeV below $BB_s\gamma$)

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

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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 $\Xi^+_c\bar{n}$. ($D^0D^+\gamma$ at 3734 MeV)

Lattice studies also suggest stable double-beauty tetraquarks

P. Bicudo, K. Cichy, A. Peters and M. Wagner, PRD **93**, 034501 (2016) [arXiv:1510.03441]:
$J^P = 1^+$ $\{bb\}[\bar{u}\bar{d}]$ meson, bound by 90^{+36}_{-43} MeV static bb, $m_\pi \approx 340$ MeV . . .

A. Francis, R. J. Hudspith, R. Lewis and K. Maltman, PRL **118**, 142001 (2017) [arXiv:1607.05214]: $J^P = 1^+$ $\{bb\}[\bar{u}\bar{d}]$ meson, bound by 189 ± 10 MeV NRQCD bb, $m_\pi \approx 164$ MeV . . .
$J^P = 1^+$ $\{bb\}[\bar{u}\bar{s}]$ and $\{bb\}[\bar{d}\bar{s}]$ mesons, bound by 98 ± 7 MeV

Unstable doubly heavy tetraquarks

Resonances in "wrong-sign" (double flavor) combinations DD, DB, BB?

$J^P = 1^+ \; \mathcal{T}^{\{cc\}++}_{[\bar{d}\bar{s}]}(4156) \to D^+ D_s^{*+}$: *prima facie evidence* for non-$q\bar{q}$ level

Double charge / double charm

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

Also, $1^+ \; \mathcal{T}^{\{bb\}}_{\{\bar{q}_k\bar{q}_l\}}(10681)^{0,-,--}$, $\mathcal{Q} = +78$ MeV $\quad 1^+ \; \mathcal{T}^{\{bc\}}_{[\bar{u}\bar{d}]}(7272)^0$, $\mathcal{Q} = +82$ MeV

$0^+ \; \mathcal{T}^{[bc]}_{[\bar{u}\bar{d}]}(7229)^0$, $\mathcal{Q} = +83$ MeV $\quad 1^+ \; \mathcal{T}^{\{cc\}}_{[\bar{u}\bar{d}]}(3978)^+$, $\mathcal{Q} = +102$ MeV

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Aside: ${}^3\mathrm{D}_3$ *and* ${}^3\mathrm{F}_4$ $c\bar{c}$ *mesons still to be found in* $D\bar{D}$*, etc.*

Production of stable tetraquarks?

Undoubtedly rare! We offer no calculation, but note

- Large yield of B_c in LHCb: 8995 ± 103 $B_c \to J/\psi \mu \nu_\mu X$ candidates in 2 fb^{-1} pp collisions at 8 TeV
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Ultimate search instrument? Future e^+e^- Tera-Z factory

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

$\rightsquigarrow$ many events containing multiple heavy quarks

Homework for experiment

Look for double-flavor resonances near threshold.

Measure cross sections for final states containing 4 heavies: $Q_i \bar{Q}_i Q_j \bar{Q}_j$.

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 Ξ_{cc} uncertainty (SELEX/LHCb)

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

Homework for theory

Develop expectations for production. A. Ali et al., "Prospects of discovering stable double-heavy tetraquarks at a Tera-Z factory," arXiv:1805.02535 $\rightarrow$ PLB (in press).

Refine lifetime estimates for stable states.

Understand how color configurations evolve with QQ (and $\bar{q}\bar{q}$) masses.
J.-M. Richard, et al., "Few-body quark dynamics for doubly-heavy baryons and tetraquarks," arXiv:1803.06155, Phys. Rev. C **97**, 035211 (2018).

Investigate stability of different body plans in the heavy-quark limit.
. . . up to $(Q_i Q_j)(Q_k Q_l)(Q_m Q_n)$: $B = 2$, but $Q_p Q_q Q_r$ color structure?

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, PLB **778**, 233 (2018).

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Lattice–NRQCD study of $bb\bar{b}\bar{b}$: No tetraquark with mass below $\eta_b\eta_b$, $\eta_b\Upsilon$, $\Upsilon\Upsilon$ 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, PRD **97**, 054505 (2018).

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.

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Unstable $Q_iQ_j\bar{q}_k\bar{q}_l$ tetraquarks with small $\mathcal{Q}$-values may be observable as resonant pairs of heavy-light mesons DD, DB, BB.