Stable, Doubly Heavy Tetraquark Mesons

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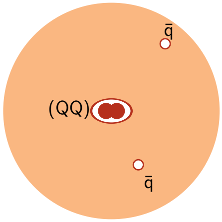

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Eichten & CQ, arXiv:1707.09575 → *PRL* DOI: 10.5281/zenodo.1123474

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

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

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

Heavier $bb\bar{q}_k\bar{q}_l$ states, double-charm states $cc\bar{q}_k\bar{q}_l$, mixed $bc\bar{q}_k\bar{q}_l$ states, will dissociate into pairs of heavy-light mesons.

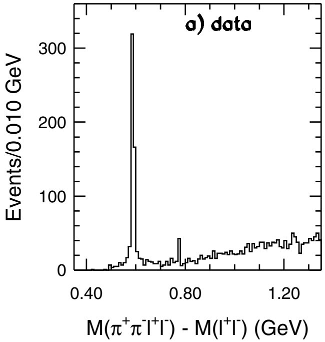
Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color-antitriplet diquarks as hadron constituents.

Prehistory (2002–2003) . . .

BELLE observes $\eta_c'(3594)$ in $B \to K K_s K^- \pi^+$ decays.

ELQ advocate B-meson gateways to missing charmonium levels
$h_c(1\,^1\mathrm{P}_1)$, $\eta_{c2}(1\,^1\mathrm{D}_2)$, and $\psi_2(1\,^3\mathrm{D}_2)$

BELLE observes $X(3872)$ in $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ decays ($D^0 \bar{D}^{*0}$ mass!)



$X(3872) \rightsquigarrow$ Renaissance in hadron spectroscopy . . .

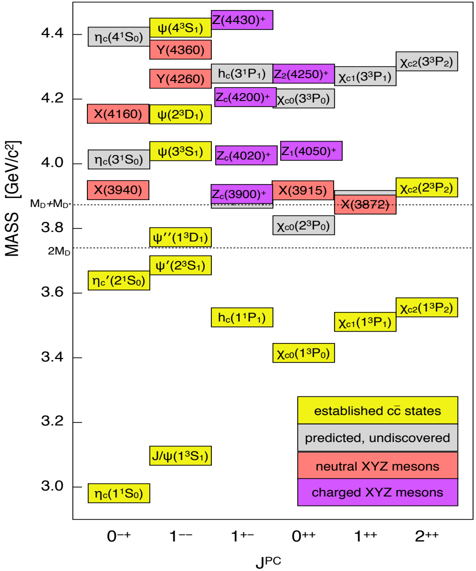
$X(3872) \neq \psi_2(1\,^3\mathrm{D}_2)$: $J^{PC} = 1^{++}$

$c\bar{c}$ state modified by coupling with open channels?
Threshold "cusp" phenomenon?
$D - \bar{D}^*$ molecule?
Tetraquark meson?

QM superposition of several Fock states
Isospin violation likely

Other new states invite hybrid ($c\bar{c}g$) interpretations, etc.

$X(3872) \rightsquigarrow$ Renaissance in hadron spectroscopy . . .



S. L. Olsen, "A New Hadron Spectroscopy," Front. Phys. (Beijing) **10**, 121 (2015) [arXiv:1411.7738].

R. F. Lebed, R. E. Mitchell, E. S. Swanson, "Heavy-Quark QCD Exotica," Prog. Part. Nucl. Phys. **93**, 143 (2017) [arXiv:1610.04528].

A. Esposito, A. Pilloni. A. D. Polosa, "Multiquark Resonances," Phys. Rept. **668**, 1 (2016) [arXiv:1611.07920].

A. Ali, J. S. Lange, S. Stone, "Exotics: Heavy Pentaquarks and Tetraquarks," Prog. Part. Nucl. Phys. **97**, 123 (2017) [arXiv:1706.00610].

Charged states invite tetraquark interpretations

Lo-o-o-o-ng history, dating to foundational papers of the quark model

G. Zweig, "An SU(3) model for strong interaction symmetry and its breaking," CERN-TH-401 (1964); "An SU(3) model for strong interaction symmetry and its breaking. 2," CERN-TH-412 (1964).

M. Gell-Mann", "A schematic model of baryons and mesons," Phys. Lett. **8**, 214–215 (1964).

Application to (light-)meson spectroscopy: broad scalars $a_0(980)$, $f_0(980)$

R. L. Jaffe, "Multi-Quark Hadrons. 1. The Phenomenology of $(Q^2\bar{Q}^2)$ Mesons," Phys. Rev. D **15**, 267 (1977); "Multi-Quark Hadrons. 2. Methods," Phys. Rev. D **15**, 281 (1977).

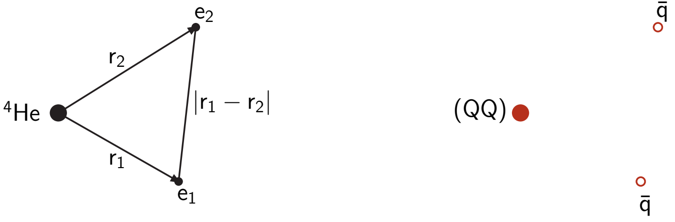
Tetraquark interpretations of XYZ complicated by many thresholds

Tetraquark advocate: L. Maiani, "Exotic Hadrons," CERN *Heavy-hadron Spectroscopy,* July 2017

Can we unambiguously demonstrate the reality of tetraquarks?

When tetraquarks resemble the helium atom . . .

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



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

half strength of $Q\bar{Q}$ attraction in color-$\mathbf{1}$

also for string tension [Nakamura & Saito]

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

Stability in the heavy-quark limit

Dissociation into two heavy-light mesons is kinematically forbidden

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

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

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

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

Stability in the heavy-quark limit

Decay to doubly heavy baryon and light antibaryon?

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

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

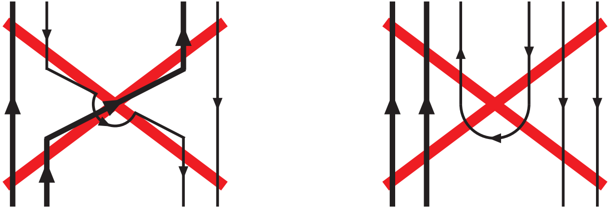
$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

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

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

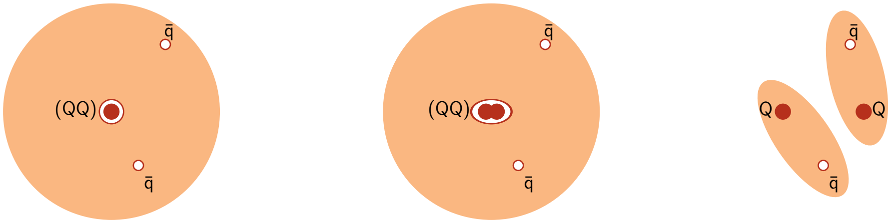


As $\overline{M} \to \infty$, stable $Q_i Q_j \bar{q}_k \bar{q}_l$ mesons must exist

Implications for the real world?

Does a tiny quasistatic diquark core make sense in this 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.

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 tetraquark masses

Masses, etc., for 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 $\delta\mathcal{K} \equiv \mathcal{K}_{(ud)} - \mathcal{K}_d$:

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

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

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

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

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

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, Ξ_{cc}; others from model calculations*

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

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

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

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

Expectations for ground-state tetraquark masses, in MeV

State	J^P	j_ℓ	$m(Q_iQ_jq_m)$	HQS relation	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	0	3663	$m(\{cc\}u) + 315$	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	0	3764	$m(\{cc\}s) + 392$	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	3663	$m(\{cc\}u) + 526$	4146, 4167, 4210	D^+D^0, D^+D^{*0} 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	0	6914	$m([bc]u) + 315$	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	0	7010	$m([bc]s) + 392$	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	1	6914	$m([bc]u) + 526$	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	0	6957	$m(\{bc\}u) + 315$	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	0	7053	$m(\{bc\}s) + 392$	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	6957	$m(\{bc\}u) + 526$	7461, 7472, 7493	BD/B^*D 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	0	10176	$m(\{bb\}u) + 306$	10482	$B^-\bar{B}^{*0}$ 10603	**−121**
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	0	10252	$m(\{bb\}s) + 391$	10643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10695/10691	**−48**
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	10176	$m(\{bb\}u) + 512$	10674, 10681, 10695	B^-B^0, B^-B^{*0} 10559, 10603	115, 78, 136

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]
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$\{bb\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	10674, 10681, 10695	$B^- B^0, B^- B^{*0}$ 10559, 10603	115, 78, 136

Compare Karliner & Rosner model results, arXiv:1707.07666.

Real-world candidates for stable tetraquarks

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

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

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

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

(3 MeV below $BB_s\gamma$)

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

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" combinations DD, DB, BB?

$\mathcal{T}^{\{cc\}++}_{[\bar{d}\bar{s}]} \to D^+ D^+_s$: *prima facie* evidence for a non-$q\bar{q}$ level

Lattice studies suggest stable double-beauty tetraquarks

P. Bicudo, K. Cichy, A. Peters and M. Wagner, "*BB* interactions with static bottom quarks from Lattice QCD," 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, "Lattice Prediction for Deeply Bound Doubly Heavy Tetraquarks," 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

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
- CMS observation of double-Υ production in 8-TeV pp collisions: $\sigma(pp \to \Upsilon\Upsilon +$ anything$) = 68 \pm 15$ pb

Ultimate search instrument? Future e^+e^- Tera-Z factory
Branching fractions $Z \to b\bar{b} = 15.12 \pm 0.05\%$, $b\bar{b}b\bar{b} = (3.6 \pm 1.3) \times 10^{-4}$

$\leadsto$ many events containing multiple heavy quarks

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 $\eta_b\eta_b$, $\eta_b\Upsilon$, $\Upsilon\Upsilon$ 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.

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 $\mathcal{Q}$-values may be observable as resonant pairs of heavy-light mesons