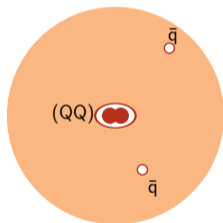


Stable, Doubly Heavy Tetraquark Mesons

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Eichten & CQ, arXiv:1707.09575 → *PRL*

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.

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.

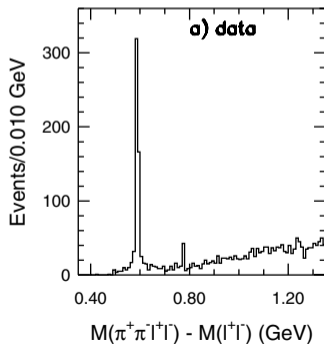
Prehistory (2002–2003) ...

BELLE observes $\eta'_c(3594)$ in $B \rightarrow KK_s K^- \pi^+$ decays.

ELQ advocate B -meson gateways to missing charmonium levels

$h_c(1^1P_1)$, $\eta_{c2}(1^1D_2)$, and $\psi_2(1^3D_2)$

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



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

$X(3872) \neq \psi_2(1^3D_2): J^{PC} = 1^{++}$

$c\bar{c}$ state modified by coupling with open channels?

Threshold “cusp” phenomenon?

$D - \bar{D}^*$ molecule?

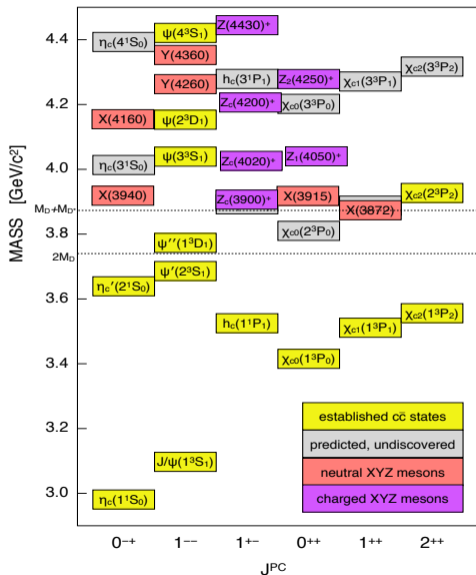
Tetraquark meson?

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).

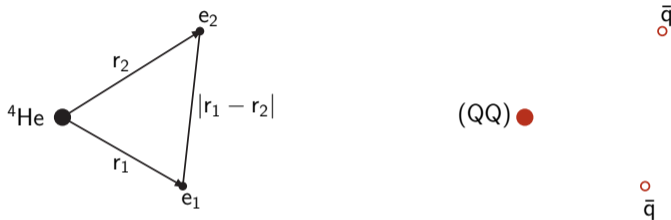
Tetraquark interpretations of XYZ complicated by many thresholds

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- $\bar{3}$
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

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

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

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

Stability in the heavy-quark limit

Decay to doubly heavy baryon and light antibaryon?

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

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

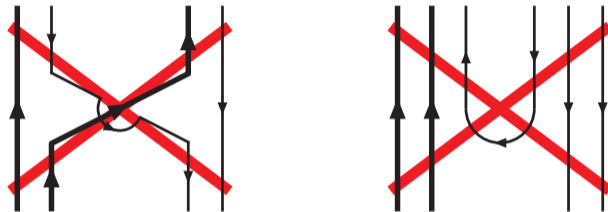
$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

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!

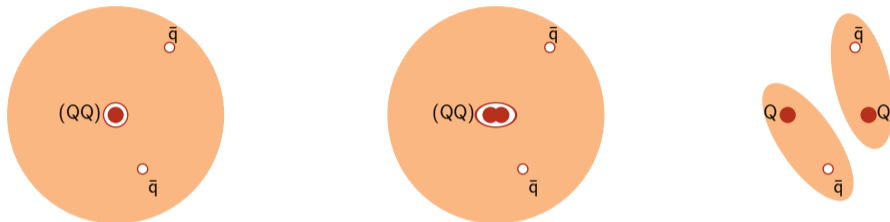


As $\bar{M} \rightarrow \infty$, stable $Q_i Q_j \bar{q}_k \bar{q}_l$ mesons must exist

Implications for the real world?

Does a tiny quasistatic diquark core make sense in 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,

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

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

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

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

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

(hyperfine + light d.o.f.)

to estimate 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
$\Lambda_c (cud)_{\bar{3}}$	0	2286.46	–	–	–	–
$\Sigma_c (cud)_6$	1	2518.41	2453.97	2496.93	64.44	0.132
$\Xi_c (cus)_{\bar{3}}$	0	2467.87	–	–	–	–
$\Xi'_c (cus)_6$	1	2645.53	2577.4	2622.82	68.13	0.141
$\Omega_c (css)_6$	1	2765.9	2695.2	2742.33	70.7	0.146
$\Xi_{cc} (ccu)_{\bar{3}}$	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
$\Lambda_b (bud)_{\bar{3}}$	0	5619.58	–	–	–	–
$\Sigma_b (bud)_6$	1	5832.1	5811.3	5825.2	20.8	0.131
$\Xi_b (bds)_{\bar{3}}$	0	5794.5	–	–	–	–
$\Xi'_b (bds)_6$	1	5955.33	5935.02	5948.56	20.31	0.128
$\Omega_b (bss)_6$	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 $\delta\mathcal{K} \equiv \mathcal{K}_{(ud)} - \mathcal{K}_d$:

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

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

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

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

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

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, Ξ_{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 a pair of heavy–light mesons case-by-case

Expectations for ground-state tetraquark masses, in MeV

State	J^P	j_ℓ	$m(Q_i Q_j q_m)$	HQS relation	$m(Q_i Q_j \bar{q}_k \bar{q}_l)$	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	$B^- D^+ / B^0 D^0$ 7146	83
$[bc][\bar{q}_k \bar{s}]$	0^+	0	7010	$m([bc]s) + 392$	7406	$B_s D$ 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

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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 $B^- \bar{B}^0 \gamma$)

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

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

(3 MeV below $BB_s \gamma$)

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

SELEX $M(\Xi_{cc}^+) = 3519 \text{ MeV} \rightsquigarrow m(\{cc\}[\bar{u}\bar{d}]) = 3876 \text{ MeV}$, 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 $DD, DB, BB?$

$\mathcal{T}_{[d\bar{s}]}^{\{cc\}++} \rightarrow D^+ D_s^+$: *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_{-43}^{+36} 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: $8995 \pm 103 B_c \rightarrow J/\psi \mu \nu_\mu X$ candidates in 2 fb^{-1} pp collisions at 8 TeV
- CMS observation of double- Υ production in 8-TeV pp collisions:
 $\sigma(pp \rightarrow \Upsilon\Upsilon + \text{anything}) = 68 \pm 15 \text{ pb}$

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

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 Q -values may be observable as resonant pairs of heavy-light mesons