Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 011005 (2019)
https://doi.org/10.7566/JPSCP.26.011005

Exotics with Heavy Quarks

Marek Karliner
School of Physics and Astronomy, Tel Aviv University, Israel
E-mail: marek@tauex.tau.ac.il

(Received May 27, 2019)

I discuss recent developments regarding new types of hadrons involving heavy quarks: hadronic molecules, doubly heavy baryons, stable tetraquarks and others. I also explain how the discovery of the doubly heavy baryon leads to a quark-level analogue of nuclear fusion, with energy release per reaction an order of magnitude greater than in ordinary fusion.

KEYWORDS: QCD, exotic hadrons, heavy quarks, hadronic molecules, tetraquarks, pentaquarks

1. Social Life of Heavy Quarks

Studying heavy exotic hadrons is somewhat similar to investigating the social life of heavy quarks. The relevant questions one would be asking in this context are (a) Who with whom? (b) For how long? (c) A short episode? or (d) "Till Death Us Do Part"? In the following I will try to answer some of the obvious concrete questions about exotic hadrons: Do they exist? If they do, which ones? What is their internal structure? How best to look for them?

Quarks are fundamental building blocks of protons, neutrons and all hadrons. Paraphrasing Orwell [1], one can say that *all quarks are equal, but heavy quarks are more equal than others*. In recent years a lot of attention has been devoted to new combinations of hadrons containing heavy quarks, including exotics [2, 3]:

- hadronic molecules, Z_b, Z_c tetraquark-like states, and more recently the LHCb pentaquark
- prediction and discovery of doubly-charmed baryon
- a stable $bb\bar{u}\bar{d}$ tetraquark

Hadrons with heavy quarks are much simpler than quarks containing only light quarks. This is for two main reasons. First, heavy quarks are almost static, i.e. non-relativistic, because with momentum $O(\Lambda_{QCD})$ they are slow and their kinetic energy is small compared with their mass. Second, their spin-dependent interactions are small, scaling like $1/m_Q$.

These properties enabled accurate predictions of the masses of baryons containing one b quark [4]. The key to the precision is the proper treatment of the spin-dependent interaction between quarks, also known as *color-magnetic* or *color-hyperfine* interaction, in analogy with the hyperfine interaction in atomic physics. For a discussion of the color-magnetic interaction see e.g. Ref. [5].

2. Narrow Exotics near Two Heavy-Light Hadron Thresholds

We begin our discussion with five exotic states very close to two heavy-light meson thresholds, listed in Table I. The four Z_b and Z_c states decay into quarkonium plus a charged pion, so they they are *manifestly exotic*, in the sense that their minimal quark content is $\bar{Q}Q\bar{d}u$, where $Q = b, c$. The $X(3872)$ is not manifestly exotic, but there are good reasons to think that its quark content is mostly $c\bar{c}q\bar{q}$, $q = u, d$.

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	$8 - 25$	$J/\psi\,\pi$	783	$\bar{D}^*D^*$	6
$\times$					$\bar{D}D$	
$\times$					$\bar{B}B$	

Table I. Five exotic states close to two-meson thresholds.

The five states in Table I share some striking characteristics:

(a) they are very close to two heavy-light meson thresholds;

(b) there are states close to pseudoscalar-vector ($\bar{D}D^*$, $\bar{B}B^*$) and vector-vector ($\bar{D}^*D^*$, $\bar{B}^*B^*$) thresholds, but conspicuously there is nothing close to the scalar-scalar threshold ($\bar{D}D$, $\bar{B}B$);

(c) their spin-parity quantum numbers are consistent with S-wave bound states of the two mesons;

(d) the energy available for decay into quarkonium + pion(s) is hundreds of MeV, yet their widths are tiny, unnaturally small for such a large phase space;

(e) the relative widths of the "fall-apart" decay modes into two heavy-light mesons are dramatically larger than decays into quarkonium + pion(s). This is despite the fact that the former have just a few MeV of phase space available for decay, while the latter have hundreds of MeV available.

Clearly something very interesting is going on in these systems. The above facts provide strong evidence that the five narrow states in Table I likely are *hadronic molecules*. In order to understand why, let us recall two possible arrangements of (say) $c\bar{c}u\bar{d}$ in an exotic hadron.

One possibility is a deuteron-like weakly bound state of two color-singlet heavy-light mesons $c\bar{d}$ and $\bar{c}u$. In this case the quarks inside each meson interact directly only with each other and not with the quarks in the other meson. The binding between the two color-singlet mesons occurs through exchange of pions and possibly other light mesons. Such a bound state is often referred to as a hadronic molecule, in analogy with two electrically neutral atoms which bind into a molecule.

A very different possibility is a tightly-bound *genuine tetraquark* in which all four quarks are in the same confinement volume and each quark interacts with the color degrees of freedom of all the other quarks. The two possibilities are schematically depicted in Fig. 1.

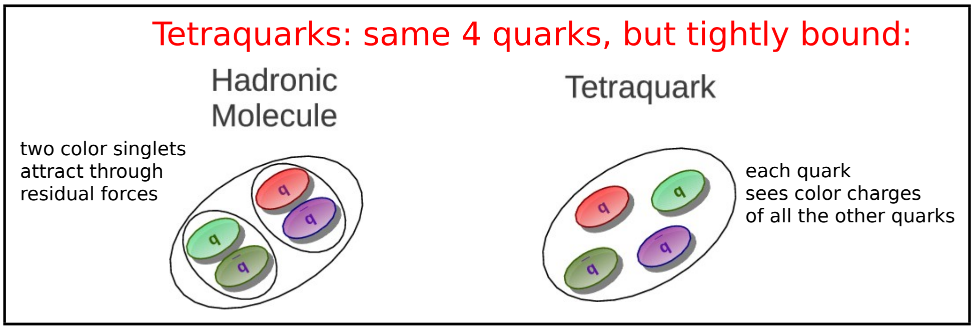

Fig. 1. A schematic depiction of a hadronic molecule vs. tightly-bound tetraquark with the same quark content. In a hadronic molecule the two color singlets interact through residual forces, while in a genuine tightly-bound tetraquark all quarks interact with each other's color charges.

A natural question is which of these two structures is more likely to describe the properties of the narrow states in Table I. The strongest hint is (d), the miniscule width of these states, despite the very large phase space available for decay into quarkonium + pions(s). According to Fermi's Golden Rule, the width of a state is given by product of the matrix element times the phase space,

$$\Gamma(|i\rangle \to |f\rangle) = |\langle f|H|i\rangle|^2 \times \Phi \tag{1}$$

Here the relevant matrix element $\langle f|H|i\rangle$ is essentially the overlap between the wave function of the exotic state and the wave function of quarkonium + pion(s).

In the molecular picture this overlap is tiny, for the following reason. Similarly to the deuteron, the binding energy ΔE is small. Therefore the radius of the bound state is large, being inversely proportional to $\sqrt{\Delta E}$. The large radius means that the c quark in one meson and the $\bar{c}$ antiquark in the other meson have a small probability of being close enough to each other to form a J/ψ. In an S-wave bound state this probability is analogous to the probability of an electron in the hydrogen atom to be inside the proton. Therefore in the molecular picture the wave function overlap is so small that it overcomes the large phase space and the narrow width is automatic.

What about a genuine tightly-bound tetraquark? In this case all four quarks are within the same confinement volume and can interact directly with each other. In particular, nothing prevents the c quark from instantly forming a color-singlet bound state with the $\bar{c}$ antiquark, hadronizing as a J/ψ. The relevant matrix element is $O(1)$. Since the phase space is huge, in this physical picture one expects large width, contrary to experiment.

Properties (a),(c) and (e) of of the states in Table I are obviously natural in the molecular picture. What about (b), the non-observation of states close to the pseudoscalar-pseudoscalar thresholds $\bar{D}D$ and $\bar{B}B$?

It is here where things get really interesting. In the binding of color-singlet hadrons one pion exchange is naturally very important, because the pion is the lightest hadron. But two pseudoscalars cannot bind through one pion exchange, because this would require a three pseudoscalar vertex which is not allowed in QCD, due to parity and angular momentum conservation.

So the molecular picture provides a natural and intuitive explanation to all the experimental data regarding the states in Table I. It is natural to ask whether there could be additional molecular states of this type. The necessary conditions for the existence of such a molecular resonance are as follows

(a) both hadrons must be heavy, as the repulsive kinetic energy is inversely proportional to the reduced mass;
(b) both must couple to pions (one of them can have $I = 0$, e.g. $\Sigma_c\bar{\Lambda}_c \underset{\pi}{\longrightarrow} \Lambda_c\bar{\Sigma}_c$);
(c) the two hadrons' spin & parity should allow one π exchange;
(d) The widths of the constituent hadrons must be smaller than the width of the resonance, $\Gamma(h_1) + \Gamma(h_2) \ll \Gamma(\text{molecule})$

The crucial insight is that the binding mechanism can in principle apply to any two heavy hadrons which couple to isospin and satisfy these conditions, *be they mesons or baryons* [6]. The relevant states are shown in Table II.

In particular, on the basis of the above considerations one expects a $\Sigma_c\bar{D}^*$ five-quark exotic baryon with minimal quark content $c\bar{c}uud$, a bit below the 4462 MeV threshold.

The pentaquark-like narrow resonance $P_c(4450)$ discovered by LHCb in the decay $\Lambda_b \to J/\psi pK^-$ fits the bill very well. Its mass is 12 MeV below the $\Sigma_c\bar{D}^*$ threshold and it has a narrow width of 39 MeV, despite the 400 MeV phase space available in its $J/\psi p$ decay channel [7].

Just like for exotic mesons, the narrow width is a problem for a tightly-bound pentaquark interpretation, given the large phase space of 400 MeV

$$\Gamma\left(P_c(4450) \to J/\psi p\right) = \left|\langle P_c(4450)|J/\psi p\rangle\right|^2 \times (\text{phase space})$$

Thresholds for $Q\bar{Q}'$ molecular states

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a]Ignoring annihilation of quarks. [b]Plus other charge states when $I \neq 0$.
[c]Based on isospin-averaged masses. [d]Thresholds differ by 27.6 MeV.

Table II. Thresholds for molecular states consisting of a hadron with a heavy quark $Q = c$ or b and an antiquark $\bar{Q}' = \bar{c}$ or $\bar{b}$, with $q = u, d$. [6]. A likely candidate for the $P_c(4450)$ discovered by LHCb [7] is marked in red.

To get $\Gamma = 39$ MeV, the matrix element must be small. But in a tightly-bound pentaquark c and $\bar{c}$ are close to each other within the same confinement volume, so overlap with J/ψ is generically large. In a molecule the narrow width is automatic: c is in Σ_c, $\bar{c}$ is in $\bar{D}^*$; they are far from each other, so overlap with J/ψ is generically small, as schematically depicted in Fig. 2.

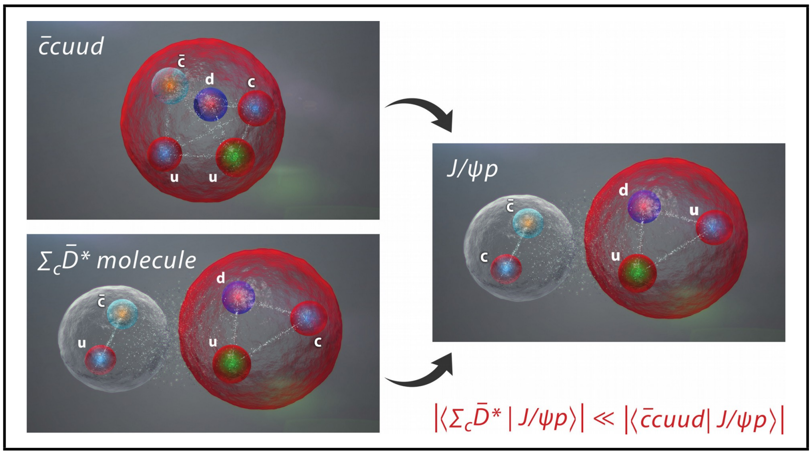

Fig. 2. Schematic illustration of the generically narrow width of the five-quark state expected in the molecular picture vs. the large width expected in tightly-bound pentaquark scheme.

For obvious reasons it is essential to confirm the LHCb findings and to observe the $P_c(4450)$ in another experiment. At the moment no other experiment has a comparable number of Λ_b-s and a suitable detector in order to repeat the LHCb analysis in the same channel. Instead, several groups proposed to look for $P_c(4450)$ as an s-channel resonance in photoproduction, $\gamma p \to J/\psi p$ [8–10]. In fixed target mode the required energy of the photon is about 10 GeV. Several fixed-target experiments are currently under way at JLab. In principle it is also possible to look for a bottom analogue of

$P_c(4450)$, a $\Sigma_b B^*$ molecule around 7.778 GeV in the reaction $\gamma p \to \Upsilon p$. But since the required lab photon energy is 65.7 GeV, it is far from clear that such an experiment is feasible.

3. Doubly Heavy Baryons QQq

Doubly-heavy baryons contain two heavy quarks and one light quark: ccq, bcq and bbq, where $q = u, d, s$. Unlike the exotic $Q\bar{Q}q\bar{q}$ and $Q\bar{Q}qqq$ states discussed in the previous section, there is nothing exotic about the doubly-heavy baryons per se. Yet, as we shall soon see, they are intimately connected with $QQ\bar{q}\bar{q}$ tetraquarks containing two heavy quarks, rather than a heavy quark and a heavy antiquark discussed in the context of hadronic molecules.

Even though it has been clear that they exist, the first doubly-heavy baryon $\Xi_{cc}^{++} = (ccu)$ was observed only in 2017, in an experimental *tour de force* by LHCb [11], with a mass of 3,621±1 MeV, rather close to our prediction 3,627±12 MeV [5] (c.f. Table III).

Within QCD the ground state $QQ'q$ baryons are stable, decaying only by weak interaction. In 2018 LHCb measured the Ξ_{cc}^{++} lifetime, obtaining $256\,^{+24}_{-22}\,$(stat) $\pm$ 14 (syst) fs, [12]. Fig. 3 shows a comparison between the LHCb measurement and theoretical predictions, including ours [5].

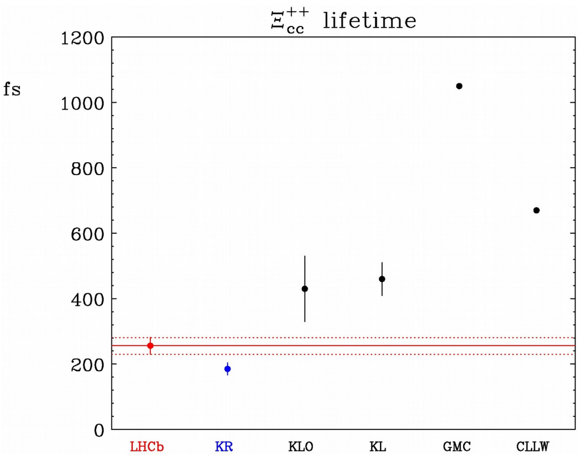

Fig. 3. Ξ_{cc}^{++} lifetime. The LHCb measurement is plotted in red, our prediction is plotted in blue. Other theoretical predictions are indicated by the initials of the authors.

Contributions to Ξ_{cc} mass

Contribution	Value (MeV)
$2m_c^b + m_q^b$	3783.9
cc binding	-129.0
$a_{cc}/(m_c^b)^2$	14.2
$-4a/m_q^b m_c^b$	-42.4
Total	3627 ± 12

The $\pm$12 MeV error estimate from average error for Qqq baryons

Table III. Contributions to the mass of the Ξ_{cc}^{++} baryon.

We computed the masses of the doubly-heavy baryons in the quark model, a phenomenological approach based on identifying the effective degrees of freedom and their interactions. Effective quark masses and quark-quark binding energy are extracted from earlier experiments and then used to make predictions.

It worked very well [4] for singly-heavy b-baryons, but for doubly-heavy baryons there is no other experiment from which one can extract the binding energy of two heavy quarks to each other. Progress became possible only with the realization that in the weak coupling limit the strength of QQ interaction in a color antritriplet is exactly one half of the interaction of $Q\bar{Q}$ in a color singlet.

We assumed that this relation holds also inside hadrons. The $Q\bar{Q}$ binding energy can then be extracted from quarkonia. It is quite large, hundreds of MeV. Our assumption has been validated by the agreement between the prediction and the experiment. A posteriori one can understand why it works well. When two heavy quarks come together, they end up quite close to each other, about 0.25 fm for cc and about 0.2 fm for bb. At such small distances the heavy quark potential $V_{QQ}(r) \propto -\alpha_s(r)/r + \sigma r$ is dominated by the Coulomb term with a small α_s. Despite the smallness of α_s, the binding energy is large, because of the singular $1/r$ term. The contributions to Ξ_{cc}^{++} mass, including the very large cc binding energy, are shown in Table III.

4. A Stable $bb\bar{u}\bar{d}$ Tetraquark

The question whether $QQ\bar{q}\bar{q}$ tetraquarks with two heavy quarks Q and two light antiquarks $\bar{q}$ are stable or unstable against decay into two $Q\bar{q}$ mesons has a long history. Until summer 2017 it had been largely undecided, mainly due to lack of experimental information about the strength of the interaction between two heavy quarks. The LHCb discovery of the doubly charmed baryon provided the crucial experimental input which allows this issue to be finally resolved.

Specifically, the mass of $\Xi_{cc}^{++} = (ccu)$ doubly-charmed baryon being close to the predicted mass validated the assumption that the binding energy of two heavy quarks Q in a color-antitriplet QQ state is half that of $Q\bar{Q}$ in a color singlet. The same theoretical toolbox that led to the accurate Ξ_{cc} mass prediction then predicts a *stable, deeply bound* $bb\bar{u}\bar{d}$ *tetraquark, far below two B meson threshold – the first manifestly exotic stable hadron* [13, 14].

The essential mechanism at work here is as follows. The heavier the quarks, the closer they are to each other in a hadron, the bigger the binding energy between them, because of the $-\alpha_s/r$ term in the heavy quark potential. When the four quarks $QQ\bar{q}\bar{q}$ are split into two $Q\bar{q}$ mesons, this QQ binding energy is lost. The QQ binding energy scales like $m_Q\alpha_s^2$, so for sufficiently large m_Q the $QQ\bar{q}\bar{q}$ tetraquark *must be bound*. The new piece of information is that, thanks to LHCb, *we now know* that the b quark is heavy enough, so that the binding energy of two b quarks in a $bb\bar{u}\bar{d}$ tetraquark is so big as to prevent its decay into two mesons.

The lowest possible mass of a $bb\bar{u}\bar{d}$ state is obtained with all four quarks in a relative S-wave and the $\bar{u}$ and $\bar{d}$ light antiquarks in a color-triplet "good" antidiquark with $S = 0$ and $I = 0$. The bb diquark must then be a color antitriplet and Fermi statistics dictates it has spin 1. The total spin and parity are then $J^P = 1^+$. The resulting configuration is very similar to a doubly-heavy baryon, c.f. Fig. 4.

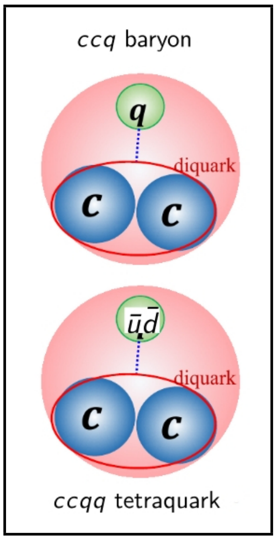

Fig. 4. Similarity between a doubly heavy QQq baryon and doubly heavy $QQ\bar{u}\bar{d}$ tetraquark. Instead of a light color-triplet quark in the baryon, in the tetraquark one has a light composite color-triplet $\bar{u}\bar{d}$ diquark.

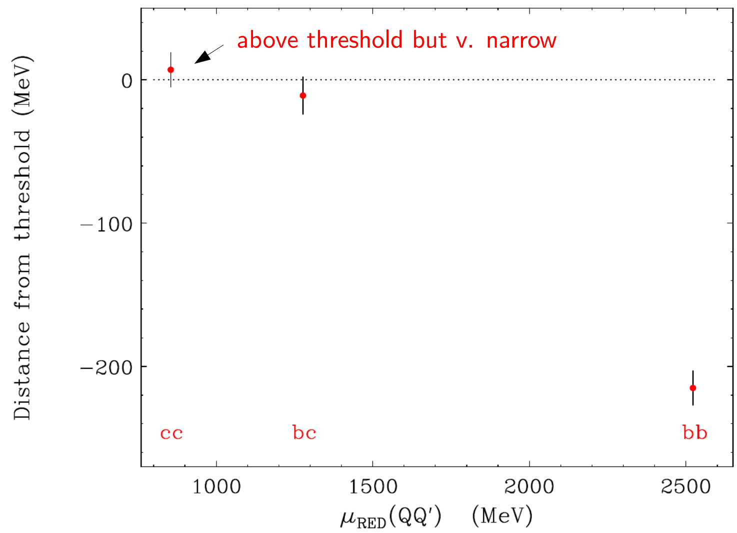

Fig. 5. Distance of the $QQ'\bar{u}\bar{d}$ tetraquarks from the corresponding $(Q\bar{u})$ $(Q'\bar{d})$ two meson thresholds.

For this configuration we use the methods of Ref. [13] to predict a doubly-bottom tetraquark $T(bb\bar{u}\bar{d})$ with J^P=1^+ at 10,389 ± 12 MeV.

Angular momentum and parity conservation in strong and EM interactions forbid a state with $J^P = 1^+$ from decaying strongly or electromagnetically into two pseudoscalars in any partial wave. Therefore $bb\bar{u}\bar{d}$ with $J^P = 1^+$ cannot decay into BB. The lowest-mass hadronic channel allowed by angular momentum and parity is BB^*, most favorably in S-wave. This channel is however kinematically closed, because the $T(bb\bar{u}\bar{d})$ mass is 215 MeV below the BB^* threshold at 10,604 MeV. $M(T(bb\bar{u}\bar{d}))$ is also 170 MeV below $2m_B$, the relevant threshold for EM decay to $B^-\bar{B}^0\gamma$.

The B mesons are the lightest states that carry open bottom, so the $bb\bar{u}\bar{d}$ tetraquark cannot decay through strong or EM interactions which conserve heavy flavor. It can only decay weakly, when one of the b quarks decays into a c quark and a virtual W^+. A typical decay is therefore $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^+(\rho^+)$, etc.

A crude estimate of the $bb\bar{u}\bar{d}$ lifetime can be obtained similarly to Ref. [5]. We assume an initial state with mass 10,389.4 MeV, a final state with $M(\bar{B}) + M(D) = 7,144.5$ MeV, a charged weak current giving rise to $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, $\tau\bar{\nu}_\tau$ and three colors of $\bar{u}d$ and $\bar{c}s$, a kinematic suppression factor

$$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x)\,,$$
$$x \equiv \{[M(\bar{B}) + M(D)]/M(bb\bar{u}\bar{d})\}^2, \tag{2}$$

a value of $|V_{cb}| = 0.04$ as in Ref. [5], and a factor of 2 to count each decaying b quark. The resulting decay rate is

$$\Gamma(bb\bar{u}\bar{d}) = \frac{18\, G_F^2 M(bb\bar{u}\bar{d})^5}{192\pi^3} F(x)|V_{cb}|^2 = 17.9\times10^{-13}\ \text{GeV}\,, \tag{3}$$

leading to a predicted lifetime $\tau(bb\bar{u}\bar{d}) = 367$ fs.

The binding energy between the two heavy quarks increases progressively as function of their mass and as a result so does the distance from the relevant two meson threshold. Fig. 5 shows the distance of the $cc\bar{u}\bar{d}$, $bc\bar{u}\bar{d}$ and $bb\bar{u}\bar{d}$ tetraquarks from the respective two meson thresholds.

The upshot is that while $J^P = 1^+$ $bb\bar{u}\bar{d}$ is deeply bound, $(bc\bar{u}\bar{d})$ with $J^P = 0^+$ is borderline bound at 7134 ± 13 MeV, 11 MeV below $\bar{B}^0D^0$, and $(cc\bar{u}\bar{d})$ with $J^P = 1^+$ is borderline unbound at 3882 ± 12 MeV, 7 MeV above the D^0D^{*+}

The inclusive production cross section of the $T(bb\bar{u}\bar{d})$ tetraquark is likely to be somewhat smaller than the corresponding cross section for the production of a doubly heavy X_{bb} baryon. This is because the bottleneck in both cases is producing two b quarks close enough to each other in momentum and ordinary space to form a bb diquark. The difference is only in the hadronization stage. To produce a Ξ_{bb} the bb diquark needs to pick up one light quark. To make a $T(bb\bar{u}\bar{d})$, the bb diquark needs to pick up a light $\bar{u}\bar{d}$ diquark. The probability for the latter is smaller than for picking up a single quark, but not dramatically so. The relevant cross sections are significantly smaller than in the charm sector, so most likely we'll see the double bottom states only after the high luminosity upgrade of the LHC.

On the other hand, LHCb has already observed Ξ_{cc}, so the experimental observation of the doubly charmed tetraquark $cc\bar{u}\bar{d}$ might be within reach.

An interesting proposal has been made to look for $T(bb\bar{u}\bar{d})$ in e^+e^- channel in future Z^0 factories [15]. The authors estimate $\mathcal{B}(Z \to T^(bb\bar{u}\bar{d}) + \bar{b}\bar{b}) = (1.4^{+1.1}_{-0.5}) \times 10^{-6}$. With $O(10^{12})$ Z^0-s this should provide a very large number of $T(bb\bar{u}\bar{d})$-s, even after all the experimental constraints are taken into account.

5. Quark-Level Analogue of Nuclear Fusion with Doubly Heavy Baryons

The large binding energy $\sim$ 130 MeV between the two c quarks inside a Ξ_{cc} doubly-charmed baryon enables a quark-rearrangement exothermic reaction [16]

$$\Lambda_c\,\Lambda_c \;\to\; \Xi_{cc}^{++}\, n \tag{4}$$

with energy release, or Q-value of 12 MeV, which is a quark-level analogue of the nuclear fusion reaction $^3\mathrm{He}\,^3\mathrm{He} \to {}^4\mathrm{He} + 2p$, schematically shown in Fig. 6.

The much larger binding energy ~ 280 MeV between two bottom quarks b causes the analogous reaction with b quarks, $\Lambda_b \Lambda_b \to \Xi_{bb} N$ to have a dramatically larger Q-value, 138 ± 12 MeV.

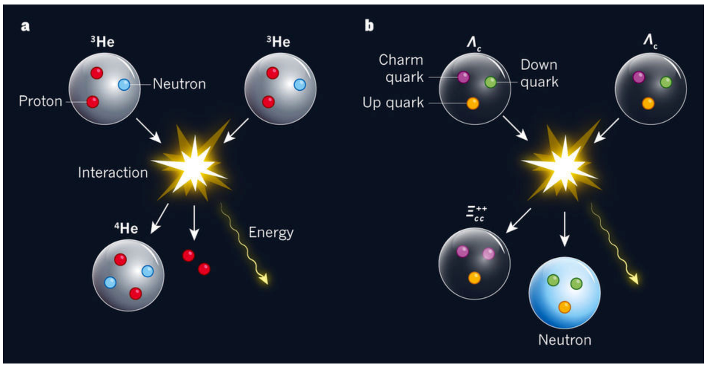

Fig. 6. A quark-level analogue of nuclear fusion. (a) Ordinary nuclear fusion, i.e. rearrangement of nucleons (b) Quark-level fusion, i.e. rearrangement of quarks inside two Λ_c baryons into a Ξ_{cc} and a neutron.

Because of the very short lifetimes of b and c quarks $O(10^{-13}\text{-}10^{-12})$ sec. reactions like eq. (4) are extremely difficult to realize experimentally. For the same reason they do not play a role in cosmology. Baryogenesis occurs $\sim 10^{-6}$ sec. after the Big Bang, by which time all primordial heavy quarks have long decayed. Analogous reactions might however play a role in the cosmology of the putative Dark Sector which includes QCD-like theories with confined "dark quarks" $\tilde{q}, \tilde{Q}$ with $m_{\tilde{q}} \lesssim \Lambda_{\widetilde{QCD}}$ and $m_{\tilde{Q}} \gg \Lambda_{\widetilde{QCD}}$. In many scenarios $\tilde{Q}$ are stable, unlike heavy quarks in the Standard Model. In such scenarios the tightly bound $\tilde{Q}\tilde{Q}\tilde{q}$ analogues of doubly-heavy baryons are *stable* and therefore eq. (4)-like chain reactions involving $\tilde{Q}$-level fusion might play a role in the cosmology of the Dark Sector.

Acknowledgements

The original research described in this talk was done in collaboration with Jon Rosner.

References

[1] G. Orwell, *"Animal Farm"*, Transaction Publishers, New Brunswick, NJ, USA, 2009.
[2] M. Karliner, J.L. Rosner and T. Skwarnicki, Ann. Rev. Nucl. Part. Sci. **68**, 17 (2018) [arXiv:1711.10626 [hep-ph]].
[3] S. L. Olsen, T. Skwarnicki and D. Zieminska, Rev. Mod. Phys. **90**, 015003 (2018) [arXiv:1708.04012 [hep-ph]].
[4] M. Karliner, B. Keren-Zur, H. J. Lipkin and J. L. Rosner, Annals Phys. **324**, 2 (2009) [arXiv:0804.1575 [hep-ph]].
[5] M. Karliner and J. L. Rosner, Phys. Rev. D **90**, 094007 (2014) [arXiv:1408.5877 [hep-ph]].
[6] M. Karliner and J. L. Rosner, Phys. Rev. Lett. **115**, 122001 (2015) [arXiv:1506.06386 [hep-ph]].
[7] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115**, 072001 (2015) [arXiv:1507.03414 [hep-ex]].
[8] Q. Wang, X. H. Liu and Q. Zhao, Phys. Rev. D **92**, 034022 (2015) [arXiv:1508.00339 [hep-ph]].
[9] V. Kubarovsky and M. B. Voloshin, Phys. Rev. D **92**, 031502 (2015) [arXiv:1508.00888 [hep-ph]].
[10] M. Karliner and J. L. Rosner, Phys. Lett. B **752**, 329 (2016) [arXiv:1508.01496 [hep-ph]].
[11] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **119**, 112001 (2017) [arXiv:1707.01621 [hep-ex]].
[12] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **121**, 052002 (2018) [arXiv:1806.02744 [hep-ex]].
[13] M. Karliner and J. L. Rosner, Phys. Rev. Lett. **119**, 202001 (2017) [arXiv:1707.07666 [hep-ph]].
[14] E. J. Eichten and C. Quigg, Phys. Rev. Lett. **119**, 202002 (2017) [arXiv:1707.09575 [hep-ph]].
[15] A. Ali, A.Y. Parkhomenko, Q. Qin and W. Wang, Phys. Lett. **B782**, 412(2018) [arXiv:1805.02535 [hep-ph]].
[16] M. Karliner and J. L. Rosner, Nature **551**, 89 (2017) [arXiv:1708.02547 [hep-ph]].