Tel Aviv University

Heavy Exotics Spectroscopy

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Exotic Hadrons and Flavor Physics, SCGP, May 31 2018

Social life of heavy quarks:

"Who with whom,

For how long ?

A "one-night stand",

Or "Till Death Us Do Part" ?

Outline

- quarks are fundamental building blocks of protons, neutrons and all hadrons
- all quarks are equal, but heavy quarks are more equal than others

new combinations with heavy quarks, incl. exotics:

- hadronic molecules, esp. LHCb pentaquark
- prediction and discovery of doubly-charmed baryon
- stable $bb\bar{u}\bar{d}$ tetraquark
- quark-level analogue of nuclear fusion
- possible similar mechanisms in dark matter sector

The big questions about exotic hadrons:

– do they exist ?

– if yes, which ones ?

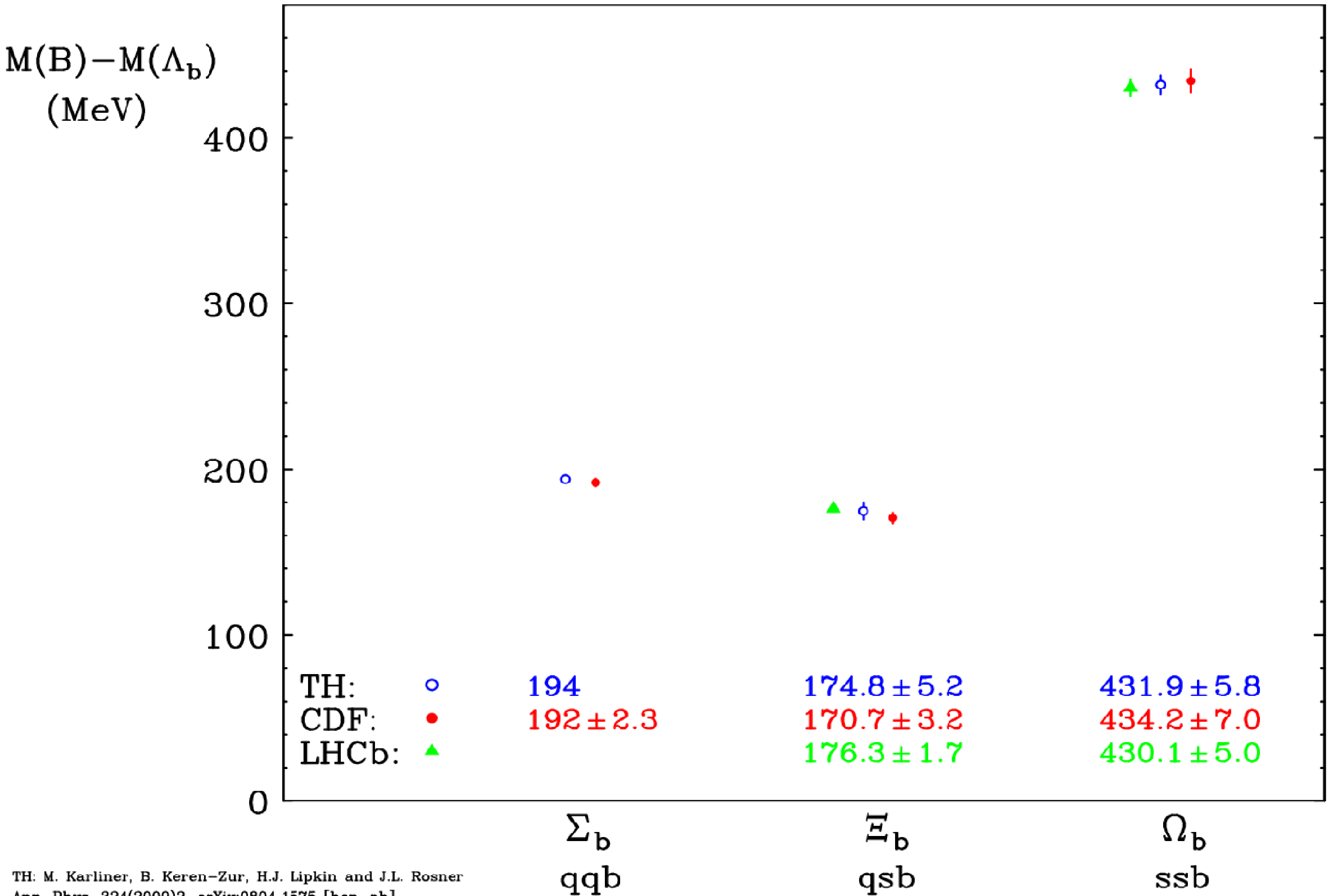
– what is their internal structure ?

– how best to look for them ?

hadrons w. heavy quarks are *much simpler:*

- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons

b−baryons spectrum − TH predictions vs EXP



TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

- Phenomenological approach
- Identify eff. d.o.f. & their interactions
- Extract model parameters from exp
- Then use them to make predictions

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3_c^*
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3_c^* } no exp info !
- $V_{HF}(cc)$ }
- $V_{HF}(cq)$
- m_q

Effective masses

in mesons:

$m_u^m = m_d^m = m_q^m = 310$ MeV, $m_c^m = 1663.3$ MeV

in baryons:

$m_u^b = m_d^b = m_q^b = 363$ MeV, $m_c^b = 1710.5$ MeV

$V(cc)$ from $V(c\bar{c})$:

$$\bar{M}(c\bar{c}:1S) \equiv [3M(J/\psi) + M(\eta_c)]/4 = 3068.6 \text{ MeV}$$

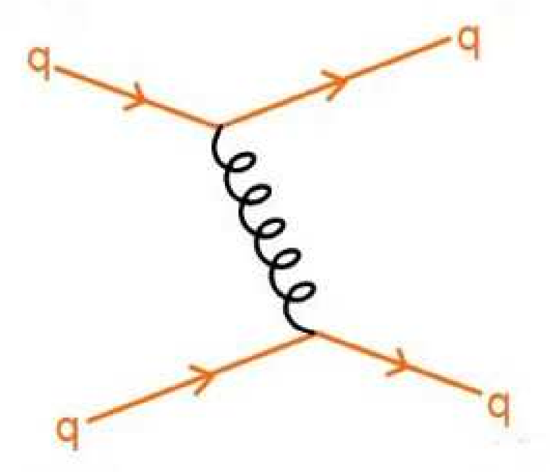
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

$$V(cc) = \frac{1}{2}V(c\bar{c}) = -129.0 \text{ MeV}.$$

in weak coupling follows
from color algebra in $1gx$

here a *dynamical assumption*:

$V(cc)$ and $V(c\bar{c})$ factorize
into color$\times$space



gluon exchange by 2 quarks

$V_{HF}(cc)$ from $V_{HF}(c\bar{c})$:

$$V_{HF}(cc) = \frac{a_{cc}}{m_c^2}$$

$$V_{HF}(c\bar{c}) = M(J/\psi) - M(\eta_c) = 113.2 \text{ MeV} = \frac{4a_{\bar{c}c}}{m_c^2}$$

assume $a_{cc} = \frac{1}{2} a_{c\bar{c}}$,

$$\Rightarrow \quad \frac{a_{cc}}{m_c^2} = 1/2 \cdot \frac{M(J/\psi) - M(\eta_c)}{4} = 14.2 \text{ MeV}$$

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 ± 12 MeV error estimate from ave. error for Qqq baryons can the strong QQ interaction stabilize

H_{QQ}: $(QQuudd)$ hexaquarks,

heavy-quark analogue of the H dibaryon?

$\Rightarrow$ below $2\Lambda_Q$

but above $\Xi_{QQ}N$

$\Rightarrow$ unstable

an ugly duckling...

The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

the first manifestly exotic stable hadron

The ugly duckling that became a swan!

Editors' Suggestion

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Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

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Recently, the LHCb Collaboration discovered the first doubly charmed baryon $\Xi_{cc}^{++} = ccu$ at 3621.40 ± 0.78 MeV, very close to our theoretical prediction. We use the same methods to predict a doubly bottom tetraquark $T(bb\bar{u}\bar{d})$ with $J^P = 1^+$ at $10\,389 \pm 12$ MeV, 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$. The $T(bb\bar{u}\bar{d})$ is therefore stable under strong and electromagnetic interactions and can only decay weakly, the first exotic hadron with such a property. On the other hand, the mass of $T(cc\bar{u}\bar{d})$ with $J^P = 1^+$ is predicted to be 3882 ± 12 MeV, 7 MeV above the D^0D^{*+} threshold and 148 MeV above the $D^0D^+\gamma$ threshold. $T(bc\bar{u}\bar{d})$ with $J^P = 0^+$ is predicted at 7134 ± 13 MeV, 11 MeV below the $\bar{B}^0D^0$ threshold. Our precision is not sufficient to determine whether $bc\bar{u}\bar{d}$ is actually above or below the threshold. It could manifest itself as a narrow resonance just at threshold.

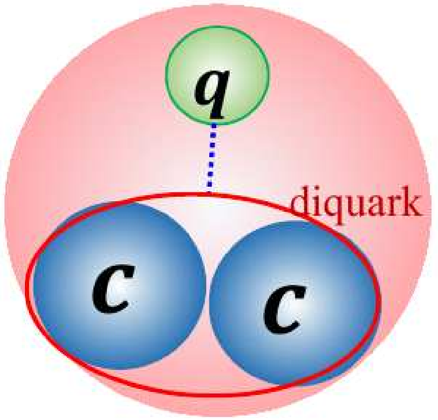
DOI: 10.1103/PhysRevLett.119.202001

Calculation of tetraquark $bb\bar{u}\bar{d}$ mass

build on accuracy of the Ξ_{cc} mass prediction

$$V(bb) = \frac{1}{2} V(\bar{b}b)$$

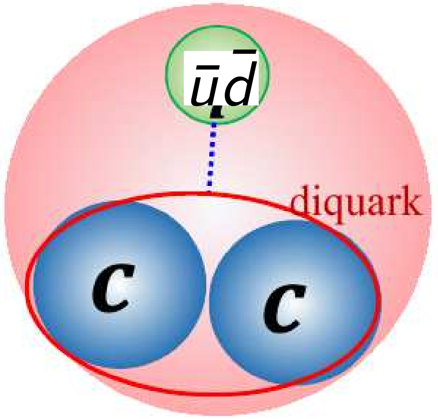
bbq baryon



to obtain lowest possible mass, assume:

- $bb\bar{u}\bar{d}$ in S-wave
- $\bar{u}\bar{d}$: $\mathbf{3_c}$ "good" antidiq., S=0, I=0

(it's the lightest one)



$\Rightarrow$ bb must be $\bar{3}_\mathbf{c}$; Fermi stats: spin 1

$(bb)_{S=1}\,(\bar{u}\bar{d})_{S=0} \Rightarrow J^P = 1^+$.

$\Rightarrow$ $(bb)\,(\bar{u}\bar{d})$ very similar to bbq baryon:

$q \leftrightarrow (\bar{u}\bar{d})$

Ξ_{cc} discovery $\Rightarrow$ quantitative validation

qualitatively $E_{binding} \sim \alpha_s^2 M_Q$

so for $M_Q \to \infty$

$QQ\bar{u}\bar{d}$ must be bound

Contributions to mass of $(bb\bar{u}\bar{d})$ Tq with $J^P = 1^+$

Contribution	Value (MeV)
$2m_b^b$	10087.0
$2m_q^b$	726.0
$a_{bb}/(m_b^b)^2$	7.8
$-3a/(m_q^b)^2$	-150.0
bb binding	-281.4
Total	10389.4 ± 12

Contributions to mass of $(cc\bar{u}\bar{d})$ Tq with $J^P = 1^+$

Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	-150.0
cc binding	-129.0
Total	3882.2 ± 12

7 MeV above $D^0 D^{+*}$ threshold,

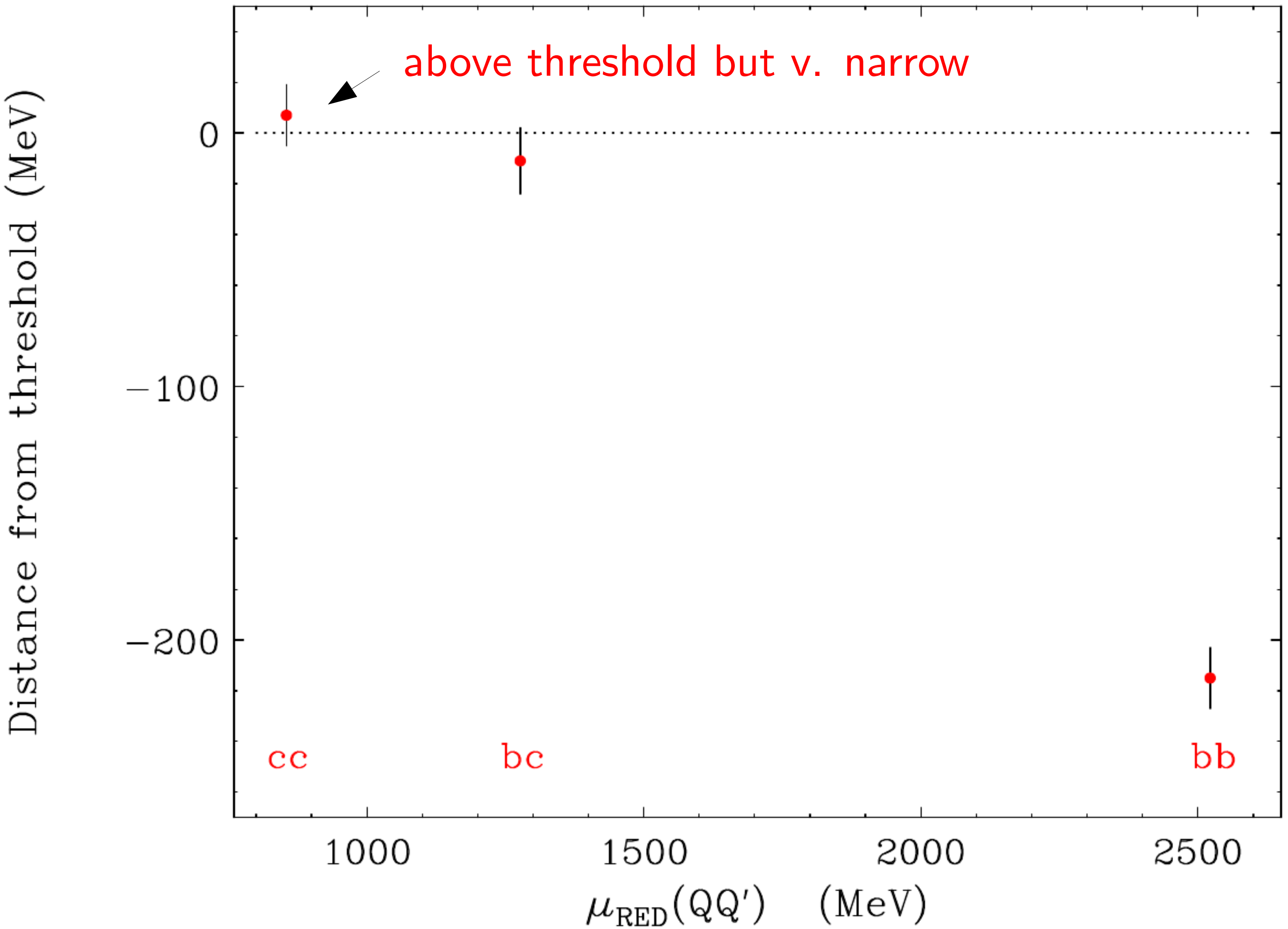
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

Contributions to mass of $(bc\bar{u}\bar{d})$ Tq* with $J^P = 0^+$

Contribution	Value (MeV)
$m_b^b + m_c^b$	6754.0
$2m_q^b$	726.0
$-3a_{bc}/(m_b^b m_c^b)$	-25.5
$-3a/(m_q^b)^2$	-150.0
bc binding	-170.8
Total	7133.7 ± 13

*lowest-mass *bc* diquark has $S=0$, so $J=0$

Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Tetraquark production

$$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lesssim \sigma(pp \to \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

$$\left.\begin{array}{l} \{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d} \end{array}\right\} \quad \begin{array}{ccc} P(\bar{u}\bar{d}) & \lesssim & P(q) \\ \mathbf{3}_c & & \mathbf{3}_c \end{array}$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
with much more $\int \mathcal{L} dt$

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LHCb observed $ccu = \Xi_{cc}^{++}$

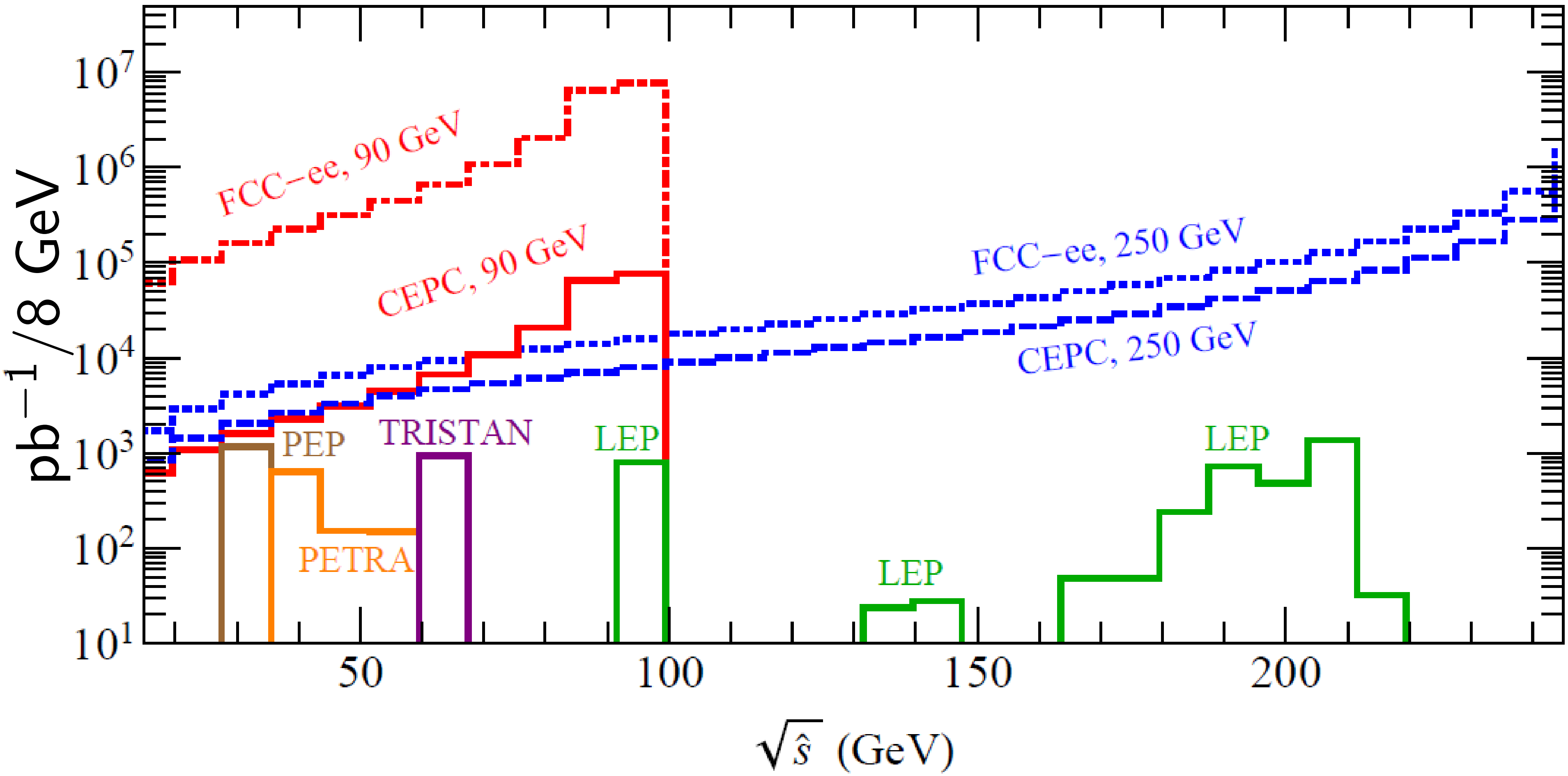
$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible, with much more $\int \mathcal{L} dt$

$T(cc\bar{u}\bar{d})$ likely narrow accessible *now*

CEPC radiative return

integrated luminosity



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

Z

gaps filled in and much more

crude estimate of $bb\bar{u}\bar{d}$ lifetime

$$M_{initial} = M(bb\bar{u}\bar{d}) = 10{,}389.4 \text{ MeV}$$

$$M_{final} = M(\bar{B}) + M(D) = 7,144.5 \text{ MeV},$$

$W^{-*} \to e\bar{\nu}_e,\ \mu\bar{\nu}_\mu,\ \tau\bar{\nu}_\tau$, 3 colors of $\bar{u}d$ and $\bar{c}s$,

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

$|V_{cb}| = 0.04$, factor of 2 to count each decaying b quark.

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

$$\tau(bb\bar{u}\bar{d}) = 367 \text{ fs.}$$

$bb\bar{u}\bar{d}$ decay channels

(a) "standard process" $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$.

$(bb\bar{u}\bar{d}) \to D^0\bar{B}^0\pi^-,\ D^+B^-\pi^-$

$(bb\bar{u}\bar{d}) \to J/\psi K^-\bar{B}^0,\ \ J/\psi\bar{K}^0B^-$.

$(bb\bar{u}\bar{d}) \to \Omega_{bc}\,\bar{p},\ \ \Omega_{bc}\,\bar{\Lambda}_c,\ \ \Xi^0_{bc}\,\bar{p},\ \ \Xi^0_{bc}\,\bar{\Lambda}_c$

In addition, a rare process where *both* $b \to c\bar{c}s$,

$(bb\bar{u}\bar{d}) \to J/\psi J/\psi K^-\bar{K}^0$.

striking signature: $2J/\psi$-s from same 2ndary vertex

(b) The W-exchange $b\bar{d} \to c\bar{u}$

e.g. $(bb\bar{u}\bar{d}) \to D^0B^-$.

$T(bb\bar{u}\bar{d})$ Summary

- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifesty exotic stable hadron
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$,
  $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
  7134 ± 13 MeV, 11 MeV below $\bar{B}^0D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
  3882 ± 12 MeV, 7 MeV above the D^0D^{*+}

two v. different types of exotics:

$Q\bar{Q}q\bar{q}$ $QQ\bar{q}\bar{q}$

e.g.

$Z_b(10610)$ $T(bb\bar{u}\bar{d})$

$\bar{B}B^*$ tightly-bound

molecule tetraquark

Exotics with $\bar{Q}Q$ vs. QQ : very different

$V(\bar{Q}Q) = 2V(QQ)$, hundreds of MeV

but *only* if $\bar{Q}Q$ color singlet

$\Rightarrow$ $\bar{Q}Q$ can immediately hadronize

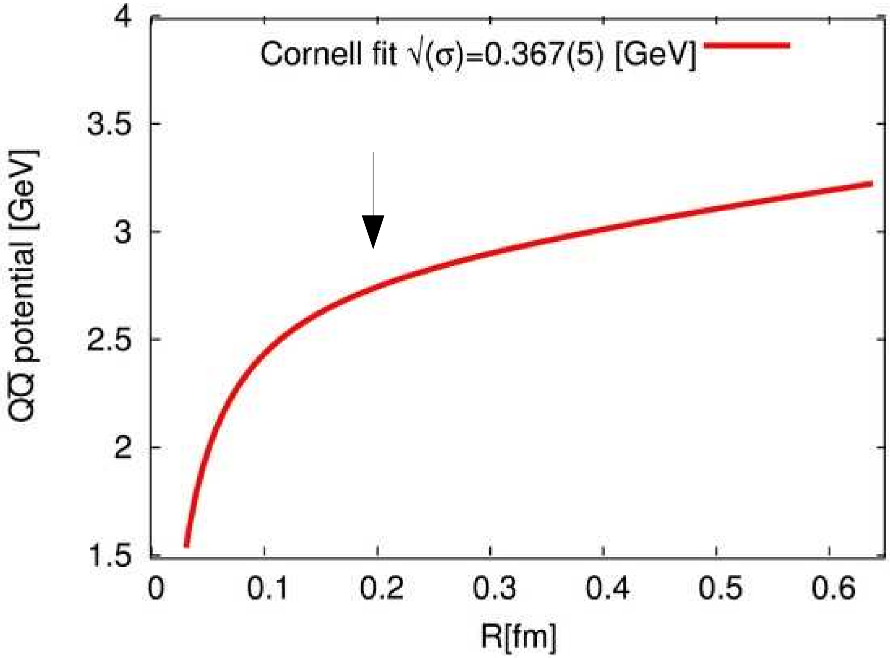
$\Rightarrow$ exotics: $\bar{Q}$ in one hadron and Q in the other

$\Rightarrow$ deuteron-like "hadronic molecules"

vs. QQ *never* a color singlet,

$\Rightarrow$ tightly bound exotics, tetraquarks

$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ GeV
$\Rightarrow R(bb) \sim 0.2$ fm
$$V(r) = -\frac{\alpha_s(r)}{r} + \sigma r$$
$\Rightarrow B(bb) \approx -280$ MeV
tightly bound, but $\bar{3}_c$,
so cannot disangage from $\bar{u}\bar{d}$



$Z_b(10610)$: $b\bar{b}u\bar{d}$

very different!

if $b\bar{b}$ compact $\Rightarrow$ color singlet:
decouple from $u\bar{d}$, $\quad Z_b \to \Upsilon\pi^+$
so only semi-stable config.,
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$

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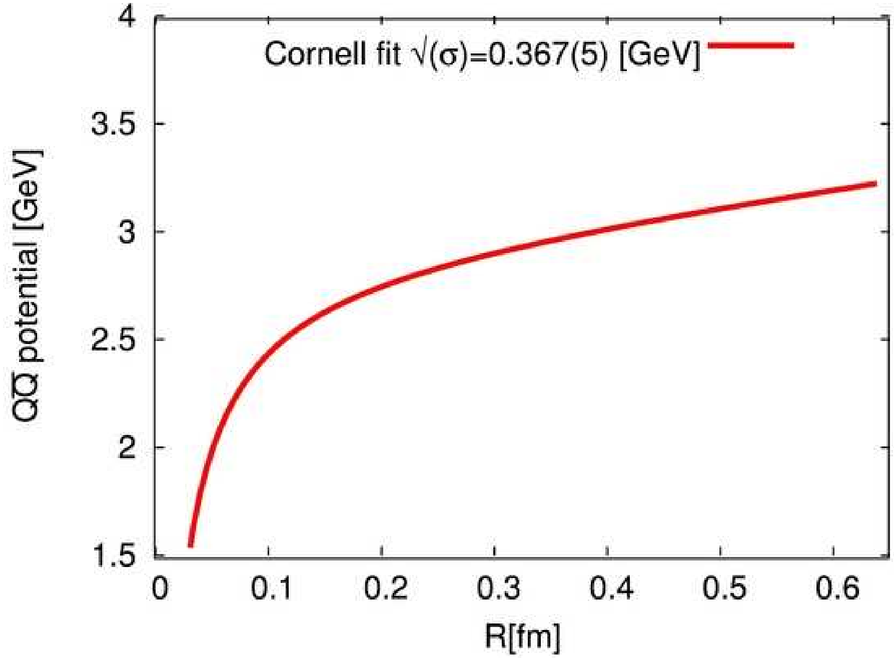

$Z_b(10610)$: $b\bar{b}u\bar{d}$ very different!
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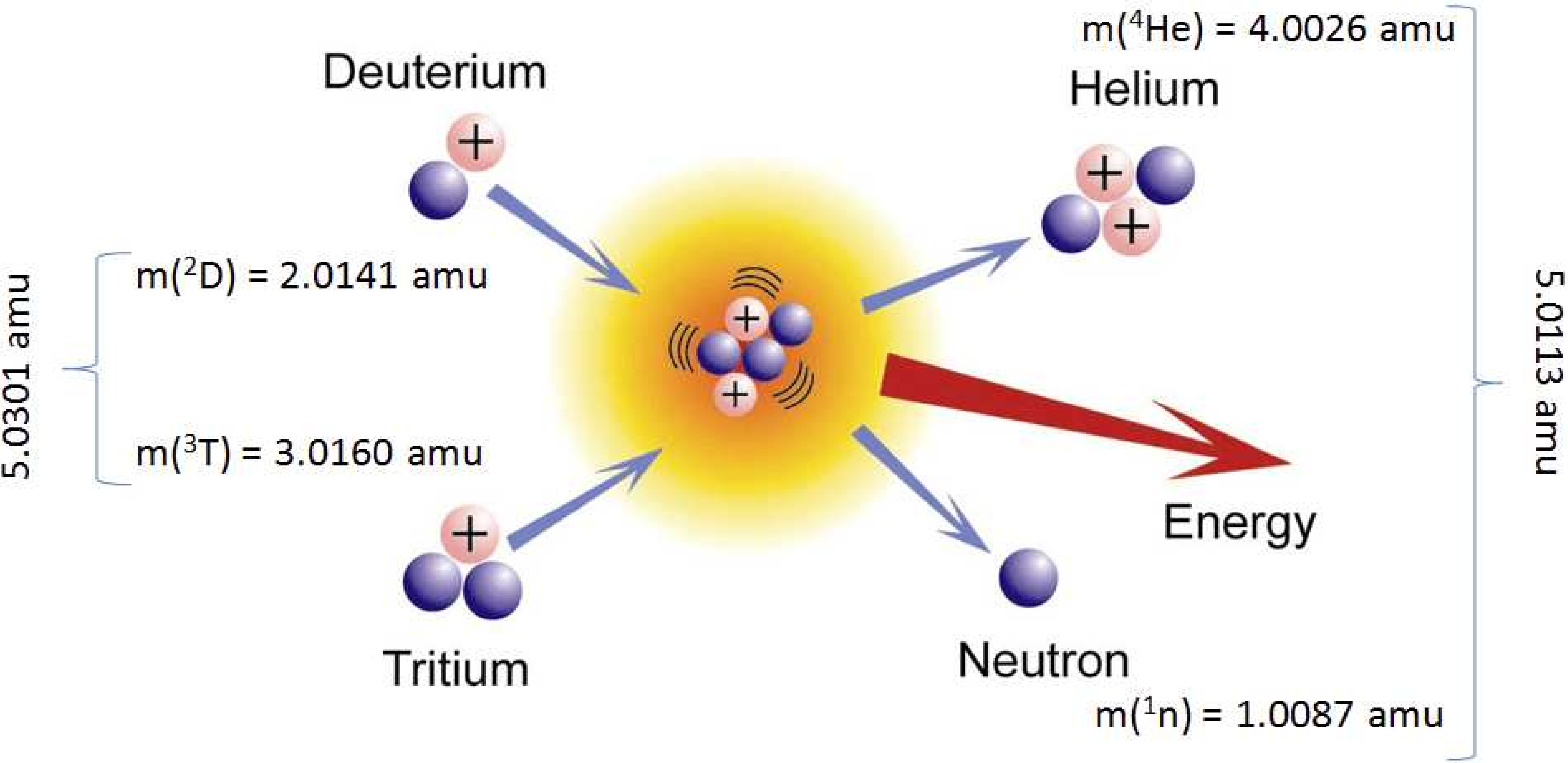
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$
bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

Quark-level analogue of nuclear fusion with doubly-heavy baryons

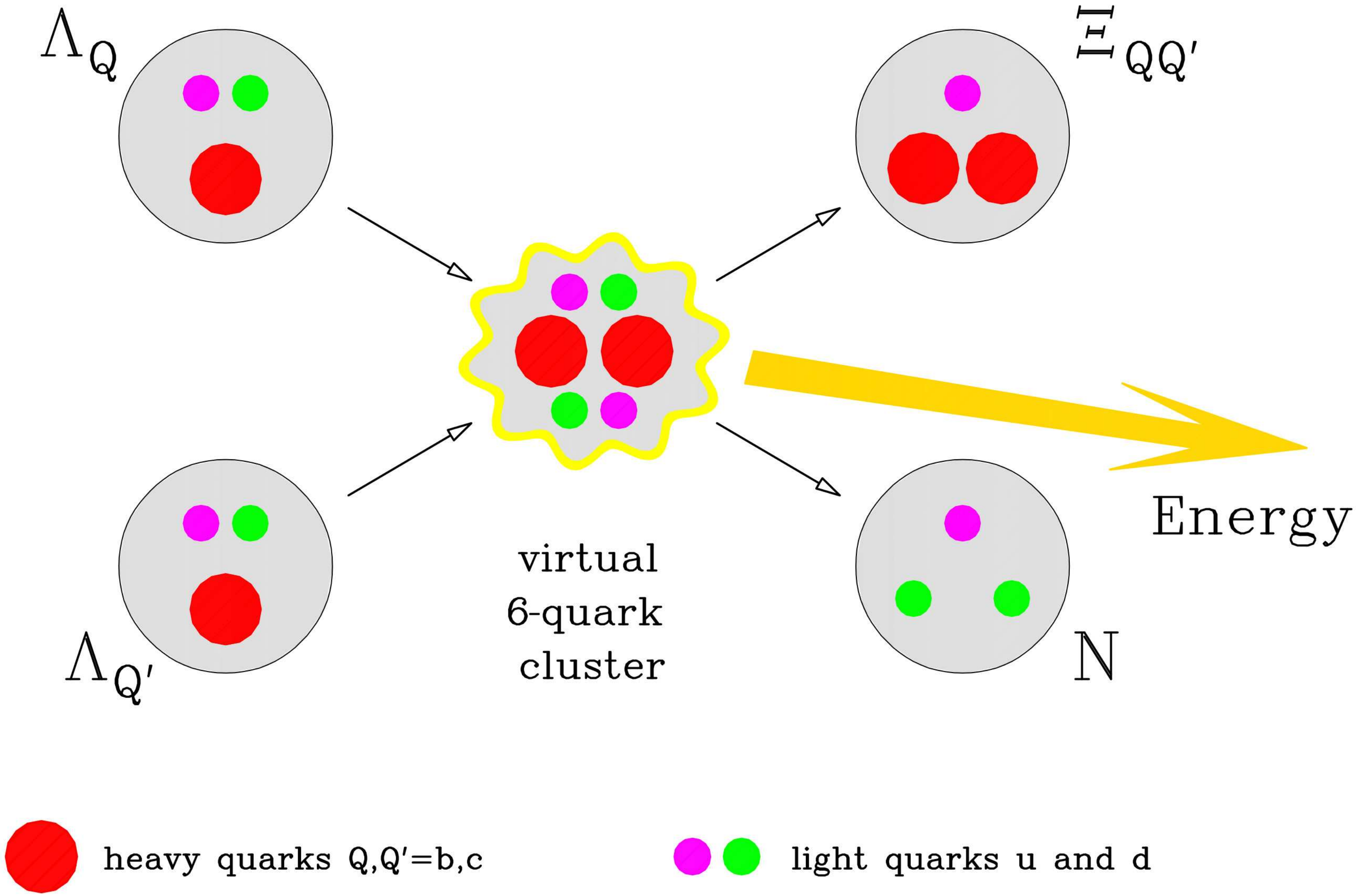
DT fusion: $\quad DT \to {}^4He\, n$



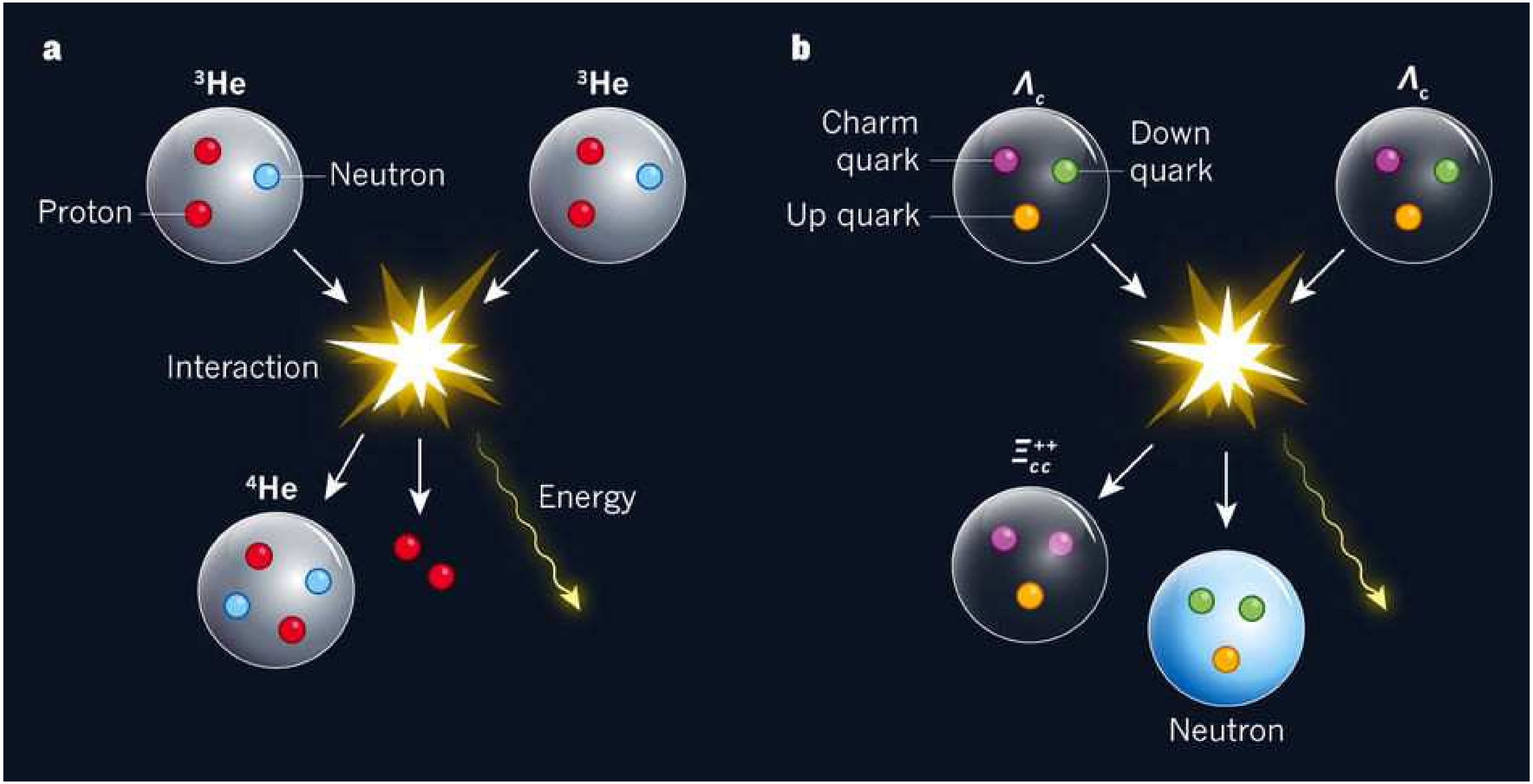
Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Nuclear fusion reactions w. light nuclei

$$
\begin{array}{lcll}
D\,T & \to & {}^4\mathrm{He}\,n & Q = 17.59 \text{ MeV}, \\
D\,D & \to & {}^3\mathrm{He}\,n & Q = \ \ 3.27 \text{ MeV}, \\
D\,D & \to & T\,p & Q = \ \ 4.04 \text{ MeV}, \\
T\,T & \to & {}^4\mathrm{He}\,2n & Q = 11.33 \text{ MeV}, \\
D\,{}^3\mathrm{He} & \to & {}^4\mathrm{He}\,p & Q = 18.35 \text{ MeV}, \\
{}^3\mathrm{He}\,{}^3\mathrm{He} & \to & {}^4\mathrm{He}\,2p & Q = 12.86 \text{ MeV}.
\end{array}
$$



Λ_Q
$\Xi_{QQ'}$
$\Lambda_{Q'}$
N
virtual
6-quark
cluster
Energy
heavy quarks Q,Q′=b,c
light quarks u and d


a
^{3}He
^{3}He
Neutron
Proton
Interaction
^{4}He
Energy
b
Λ_c
Λ_c
Charm quark
Down quark
Up quark
Ξ_{cc}^{++}
Neutron

Nature,
Nov 2, 2017

doi:10.1038/nature24289

Quark–level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner[1] & Jonathan L. Rosner[2]

The essence of nuclear fusion is that energy can be released by the rearrangement of nucleons between the initial- and final-state nuclei. The recent discovery[1] of the first doubly charmed baryon Ξ_{cc}^{++}, which contains two charm quarks (c) and one up quark (u) and has a mass of about 3,621 megaelectronvolts (MeV) (the mass of the proton is 938 MeV) also revealed a large binding energy of about 130 MeV between the two charm quarks. Here we report that this strong binding enables a quark-rearrangement, exothermic reaction in which two heavy baryons (Λ_c) undergo fusion to produce the doubly charmed baryon Ξ_{cc}^{++} and a neutron n ($\Lambda_c\Lambda_c \to \Xi_{cc}^{++} n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium–tritium nuclear fusion reaction (DT $\to$ ^{4}He n). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($\Lambda_b\Lambda_b \to \Xi_{bb}^0 n$) to have a much larger energy release of about 138 MeV. We suggest some experimental setups in which the highly exothermic nature of the fusion of two heavy-quark baryons might manifest itself. At present, however, the very short lifetimes of the heavy bottom and charm quarks preclude any practical applications of such reactions.

The mass of the doubly charmed baryon Ξ_{cc}^{++} observed in the LHCb experiment[1] 3621.40 ± 0.78 MeV is consistent with several predictions[2], including that of $3{,}627 \pm 12$ MeV (an extensive list of other predictions can be found in refs 1 and 2). The essential insight of ref. 2 is the large binding energy B of the two heavy quarks (the charm c or bottom b quarks) in a baryon, $B(cc) = 129$ MeV and $B(bb) = 281$ MeV. To a very good approximation, this binding energy is half of the quark–antiquark binding energy in their bound states, which are known as quarkonia. This 'half' rule is exact in the one-gluon-exchange limit and has now been validated by the measurement of the Ξ_{cc}^{++} mass. Its successful extension beyond weak coupling implies that the heavy quark potential factorizes into a colour-dependent and a space-dependent part, with the latter being the same for quark–quark and quark–antiquark pairs. The relative factor of 1/2 then results from the colour algebra, just as in the weak-coupling limit.

The large binding energy between heavy quarks has some important implications, such as the existence of a stable $bb\bar{u}\bar{d}$ tetraquark (where $\bar{u}$ and $\bar{d}$ are antiup and antidown quarks, respectively) with spin–parity[3] $J^P = 1^+$ 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$, where B^- is a spinless meson composed of $b\bar{u}$, $\bar{B}^{*0}$ is a spin-1 meson composed of $b\bar{d}$, $\bar{B}^0$ is a spinless meson composed of $b\bar{d}$ and γ is a photon. Another important consequence is the existence of a quark-level analogue of nuclear fusion. Consider the quark-rearrangement reaction

$$\underbrace{\Lambda_c}_{cud}\underbrace{\Lambda_c}_{cud} \to \underbrace{\Xi_{cc}^{++}}_{ccu}\underbrace{n}_{ddu} \qquad (1)$$

where the quarks are indicated below each baryon. This is a fusion of two singly heavy baryons into a doubly heavy baryon and a nucleon. The masses of all of the particles in reaction (1) are known and the energy release ΔE is 12 MeV, as shown in Table 1.

The exothermic reaction (1) is the quark-level analogue of the well known exothermic nuclear fusion reactions between the lightest nuclei, which contain two or three nucleons[4], with quarks playing the part of the nucleons, hadrons playing the part of the nuclei and the doubly heavy baryon playing the part of ^{4}He:

$$\begin{aligned} &\mathrm{DT} \to {}^4\mathrm{He}\, n, && \Delta E = 17.59\ \mathrm{MeV} \\ &\mathrm{DD} \to {}^3\mathrm{He}\, n, && \Delta E = 3.27\ \mathrm{MeV} \\ &\mathrm{DD} \to \mathrm{T}\, p, && \Delta E = 4.04\ \mathrm{MeV} \\ &\mathrm{TT} \to {}^4\mathrm{He}\, 2n, && \Delta E = 11.33\ \mathrm{MeV} \\ &\mathrm{D}^3\mathrm{He} \to {}^3\mathrm{He}\, p, && \Delta E = 18.35\ \mathrm{MeV} \\ &{}^3\mathrm{He}^3\mathrm{He} \to {}^4\mathrm{He}\, 2p, && \Delta E = 12.86\ \mathrm{MeV} \end{aligned} \qquad (2)$$

where D denotes a deuteron, T represents a triton and p stands for proton. Reaction (1) involves two hadrons with three quarks each, rather than two nuclei with two or three nucleons each, as shown schematically in Fig. 1, which also depicts the analogous reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{b, c\}$. The energy release ΔE of reaction (1) is of a similar order of magnitude to those of reactions (2).

Table 1 lists the ΔE values for four reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{s, c, b\}$. The trend is clear: ΔE increases monotonically with increasing quark mass. The reaction

$$\Lambda\Lambda \to \Xi N \qquad (3)$$

is endothermic with $\Delta E = -23$ MeV. Reaction (1) is exothermic with $\Delta E = +12$ MeV, whereas the reaction

$$\Lambda_b\Lambda_b \to \Xi_{bb}N \qquad (4)$$

is expected to be strongly exothermic with $\Delta E = +138 \pm 12$ MeV. Finally, the reaction

$$\Lambda_b\Lambda_c \to \Xi_{bc}N \qquad (5)$$

is expected to have $\Delta E = +50 \pm 13$ MeV, between the values for the cc and bb reactions (1) and (4). The latter two estimates of ΔE (for reactions (4) and (5)) rely on predictions of the Ξ_{bb} and Ξ_{bc} masses[2].

As already mentioned, the dominant effect that determines ΔE is the binding between two heavy quarks. Because these quarks interact through an effective two-body potential, their binding is determined by their reduced mass, $\mu_{red} = m_Q m_{Q'}/(m_Q + m_{Q'})$, where m_Q and $m_{Q'}$ are the masses of the individual quarks. In Fig. 2, we plot ΔE versus $\mu_{red}(QQ')$. The effective quark masses are as in ref. 2: $m_s = 538$ MeV, $m_c = 1{,}710.5$ MeV and $m_b = 5{,}043.5$ MeV. The straight-line fit $\Delta E = -44.95 + 0.0726\mu_{red}$ (dot-dashed line) describes the data well, which shows that, to a good approximation, ΔE depends linearly on the reduced mass.

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LHCb measured $M(X_{cc}^{++}) = 3621.4 \pm 0.78$ MeV

$\Rightarrow$ Q-value of the reaction:

$$\Lambda_c \ \Lambda_c \quad \rightarrow \quad \Xi_{cc}^{++} \ n, \qquad Q = 12 \text{ MeV}$$

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robust estimate of Ξ_{bb}^{0} mass, so expect

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$bud\ bud \qquad\qquad bbu\ ddu$

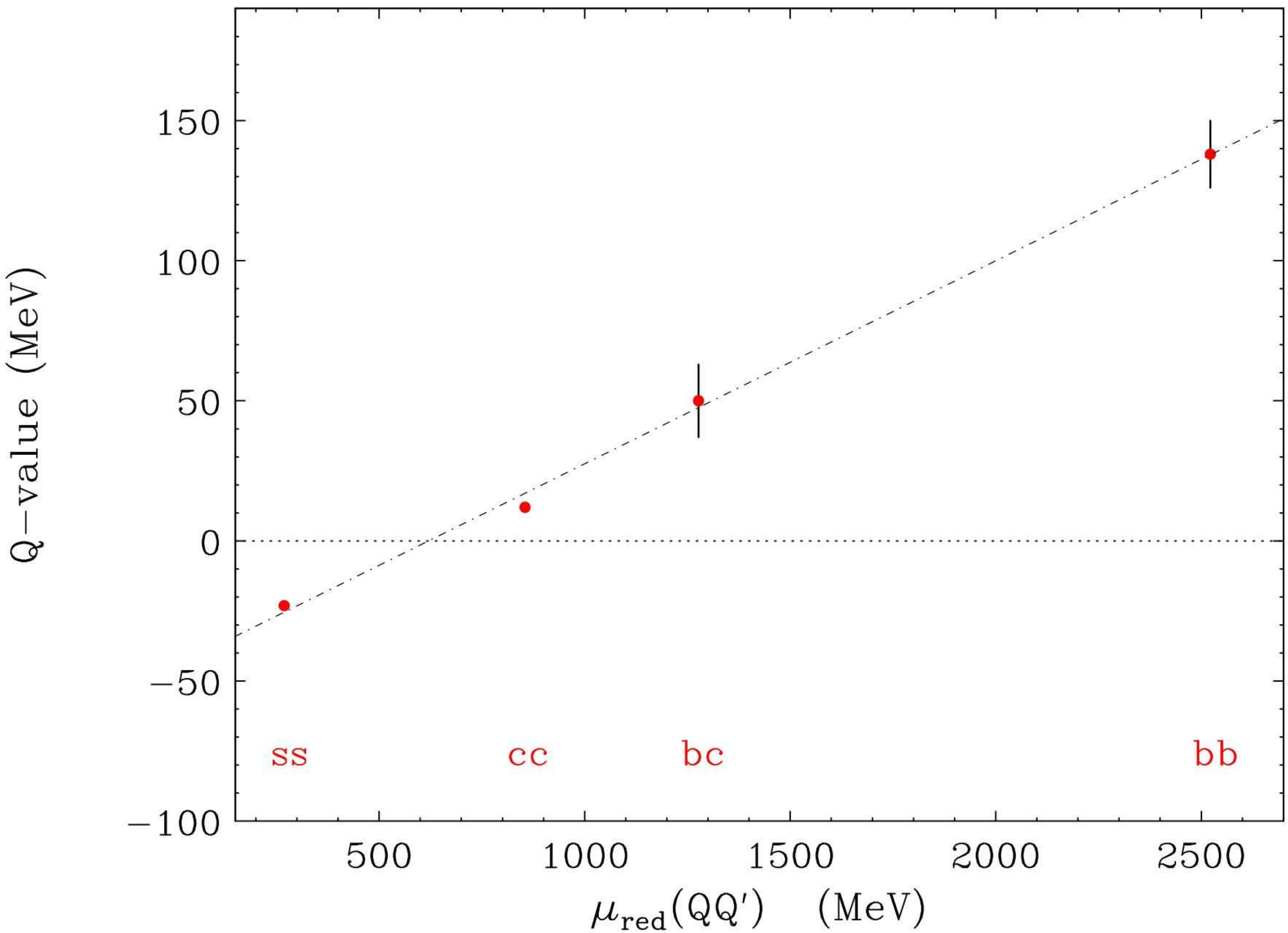
But no chain reaction, as $\tau(Q) \sim 10^{-13}$ sec

Table I

Q value in the reaction $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$.

Observable (MeV)	$\mathcal{Q}, \mathcal{Q}' = s$	$\mathcal{Q}, \mathcal{Q}' = c$	$\mathcal{Q}, \mathcal{Q}' = b$	$\mathcal{Q} = b, \mathcal{Q}' = c$
$M(\Lambda_\mathcal{Q})$	1115.7	2286.5	5619.6	5619.6, 2286.5
$M(\Xi_{\mathcal{Q}\mathcal{Q}'})$	1314.9[a]	3621.4 ± 0.78	10162 ± 12[b]	6917 ± 13[c]
Q-value	-23.1	$+12.0 \pm 0.78$	$+138 \pm 12$	$+50 \pm 13$

[a] To optimize the Q-value we take here $\Xi^0(ssu)$, $N{=}n$, because $M[\Xi^-(ssd)]$ is 7 MeV larger.
[b] Ξ_{bb} mass prediction from Ref. [2].
[c] Average of the two values in Table XI of Ref. [2].



Q-value in the quark-level fusion reactions $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$, plotted against the reduced masses of the doubly-heavy diquarks $\mu_{red}(\mathcal{Q}\mathcal{Q}')$. The dot-dashed line denotes a linear fit $Q = -44.95 + 0.0726\, \mu_{red}$.

doubly-strange hypernuclei might be produced in

$$K^- \; {}^{16}\mathrm{O} \to K^+ \; {}^{16}_{\Lambda\Lambda}\mathrm{C} \quad \equiv \quad {}^{16}\mathrm{O}(K^-, K^+)^{16}_{\Lambda\Lambda}\mathrm{C}$$

ongoing exp. at J-PARC.

Suggest bottom analogue:

$$B^- \; {}^{16}\mathrm{O} \to B^+ \; {}^{16}_{\Xi^-_{bb}}\mathrm{C}\,.$$

$E(bb) \approx 280$ MeV $\Rightarrow$ v. high Q-value

main challenge:
$\tau(B^-) = 1.6 \times 10^{-12}$ s,
$\tau(B^-) \cdot c \approx 0.5$ mm

Maybe also charm analogue

$$D^{+}\ {}^{N}\!A \to D^{-}\ {}_{\Xi_{cc}^{++}}^{N}\!A'$$

both bottom and charm

in heavy ion collisions ?

Possible similar mechanisms in DM sector

QCD-like theories w. confined "dark quarks" $\tilde{q},\tilde{\mathcal{Q}}$

$m_{\tilde{q}} \lesssim \Lambda_{\widetilde{QCD}}$, m$_{\tilde{\mathcal{Q}}}$ v. large

in many scenarios $\tilde{\mathcal{Q}}$ stable, unlike Q in SM

$\Rightarrow$ *stable* tightly-bound $\tilde{\mathcal{Q}}\tilde{\mathcal{Q}}\tilde{q}$

$\Rightarrow$ chain reaction involving $\tilde{\mathcal{Q}}$-level fusion

SUMMARY

- narrow exotics with $Q\bar{Q}$:
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$ molecules

– *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450)$ $\Rightarrow$ photoproduction
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$

- doubly charmed baryon found exactly where predicted

  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq)$, (bbq)

- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !

- $cc\bar{c}\bar{c}$ @ 6,192$\pm$25 MeV, $bb\bar{b}\bar{b}$ @ 18,826$\pm$25 MeV $\Rightarrow 4\ell$

- quark-level analogue of nuclear fusion

- possible similar mechanisms in dark matter sector

exciting new spectroscopy awaiting discovery

Addendum:

$\Omega\Omega$ (barely) bound state from lattice QCD?

$E_{\text{binding}} = 1.6(6)^{+0.7}_{-0.6}$ MeV

$m_\pi = 146$ MeV, $V = (8.1\ \text{fm})^3$, $a \simeq 0.0846$ fm

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Most Strange Dibaryon from Lattice QCD

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The $\Omega\Omega$ system in the $^1S_0$ channel (the most strange dibaryon) is studied on the basis of the $(2+1)$-flavor lattice QCD simulations with a large volume $(8.1\ \text{fm})^3$ and nearly physical pion mass $m_\pi \simeq 146$ MeV at a lattice spacing of $a \simeq 0.0846$ fm. We show that lattice QCD data analysis by the HAL QCD method leads to the scattering length $a_0 = 4.6(6)(^{+1.2}_{-0.5})$ fm, the effective range $r_{\text{eff}} = 1.27(3)(^{+0.06}_{-0.03})$ fm, and the binding energy $B_{\Omega\Omega} = 1.6(6)(^{+0.7}_{-0.6})$ MeV. These results indicate that the $\Omega\Omega$ system has an overall attraction and is located near the unitary regime. Such a system can be best searched experimentally by the pair-momentum correlation in relativistic heavy-ion collisions.

Suggest search in heavy ion collisions

through pair-momentum correlation

from which one can extract scattering length.

Perhaps applicable to BB^* scattering length?