Doubly-heavy tetraquark bound states and resonances

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Introduction

- T_{cc} discovered last summer by LHCb at CERN
- Predicted years ago (1981), confirmed and refined in several further studies (QCDSR, lattice, ...)
- Also some “rediscoveries” without credit to the earlier papers
- Several extensions already studied such as $cc\bar{u}\bar{s}$, etc.
- Here we concentrate on $QQ\bar{q}\bar{q}$, for which there are already some predictions, in particular Oka et al. (published), and Vijande et al.
- Main predictions:
  - Deeply bound ground state with $I = 0$ and $J^P = 1^+$ dominated by color $(3, \bar{3})$, spin $[(cc)_1, (\bar{u}\bar{d})_0]_1$.
  - A few near-threshold states with another structure
- Weak decay of $bb\bar{u}\bar{d}$
  $\tau(bb\bar{u}\bar{d} > \tau(B), \tau(\Lambda_b), \tau(\Xi_{bb})$??

The onset of chromoelectricity in spectroscopy

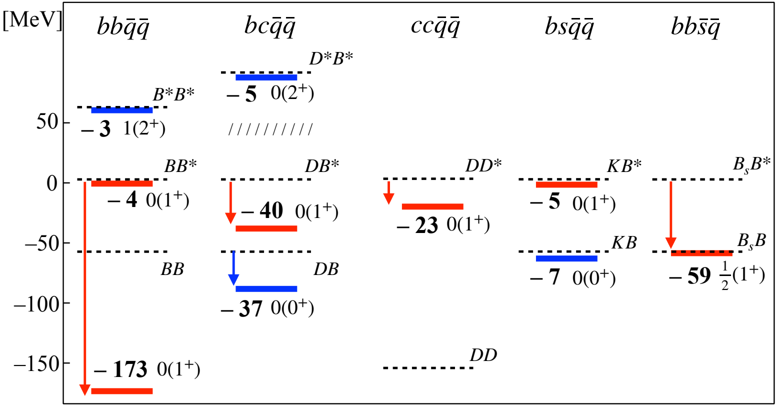
- Multiquarks in the late 70s: chromomagnetism
- For instance, Jaffe:
  - hierarchy of scalar mesons
  - speculations on the $H(uuddss)$
- 1981: Ader et al.: another mechanism: chromoelectricity
- $QQ\bar{q}\bar{q}$ becomes stable if M/m is large enough
- Even in absence of spin forces
- Striking analogy with atomic physics:
  $M^+M^+m^-m^-$ more stable than $\mu^+\mu^+\mu^-\mu^-$
- Favorable symmetry breaking

First estimates of T_{cc}^+

- Zouzou et al., Heller et al., Semay et al., Rosina et al., Barnea et al., Brink et al. ...
- Chromoelectric effect not sufficient
- Also chromomagnetic in the light sector: $\bar{u}\bar{d}$ in $I = S = 0$ (col. $\bar{3}$)
- Hence $cc\bar{u}\bar{d}$ vs. its threshold DD^*
  - benefits of the cc attraction,
  - benefits of the $\bar{u}\bar{d}$ attraction
- Such configuration ($QQ\bar{u}\bar{d}$) is rather unique. No proliferation of stable multiquarks in constituent models.

bc and other sectors

Meng et al. , using the AP1 model of Semay et al.



bc and other sectors

This model AP1 is too attractive. Alternative AL1 also slightly too attractive

state (I, J^P)	AL1	AP1
$cc\bar{q}\bar{q}$ $(0, 1^+)$	-7	-23
$bb\bar{q}\bar{q}$ $(0, 1^+)$	-144	-173
$bb\bar{q}\bar{q}$ $(1, 2^+)$	$+1$	-3
$bc\bar{q}\bar{q}$ $(0, 0^+)$	-23	-40
$bc\bar{q}\bar{q}$ $(0, 2^+)$	-3	-5

$bb\bar{s}\bar{q}$ bound in most models.

The T_{bb} sector

- In constituent models T_{bb} more deeply bound
- Same mechanism as $B + \bar{B} - b\bar{b} > D + \bar{D} - c\bar{c}$
- Referred to as flavor independence
- Again $J^P = 1^+(I = 0)$ for the ground state, with a dominant color $3\bar{3}$ structure and spin $(1, 0)$ in the $bb, \bar{u}\bar{d}$ basis
- Due to coherent CE + CM effects
- Typically 180 MeV below $B + B^*$
- Question: excitations?
- Hardly radial excitation:
  - other J^P?
  - other I
  - other inner structure for $J^P = 1^+(I = 0)$?

Real scaling (stabilization)

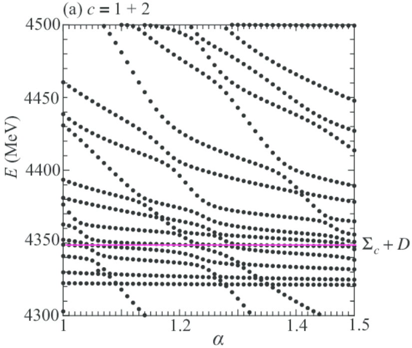
- Bound state: compact wf, which can be approximated by a variational approach,i.e., solve $H\,\Psi = E\,\Psi$ via

$$\Psi = \lim_{N\to\infty} \Psi^{(N)} = \sum_{n}^{N} \gamma_n \exp\left(-\sum a_{ij}^{(n)} \boldsymbol{x}_i.\boldsymbol{x}_j\right)$$

  with suitable optimization of the linear parameters γ_n and non-linear $a_{ij}^{(n)}$, where $\boldsymbol{x}_1, \ldots$ is a set of Jacobi coordinates.
- For the ground state, one minimizes the energy
- For the first excited, one minimizes the second energy, etc.
- In the continuum, one searches stationary states, by scaling $\boldsymbol{x}_i \to \alpha\, \boldsymbol{x}_i$ selected Jacobi coordinates
- Alternatives: complex scaling, search for complex poles, etc.

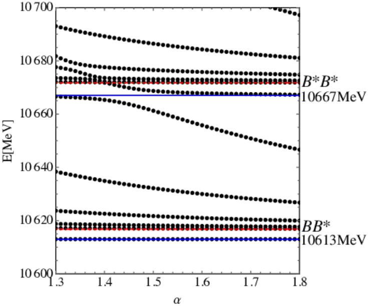
Real scaling (stabilization)

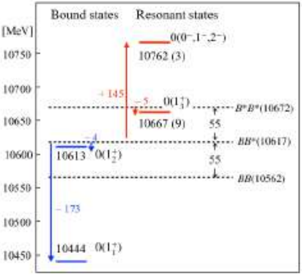
- Real scaling often used for electron scattering and other pbs of molecular phys.
- Applied by a Japanese group for pentaquark
- Other groups in China, now



Real scaling applied to pentaquark

The T_{bb} sector



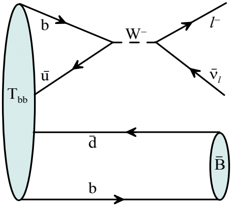


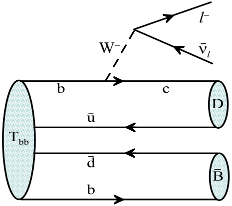
- Recent study by Oka et al., with potential by Semay et al.
  - Ground state at 173 MeV below BB^*.
  - Another b.s. $0(1^+)$ 4 MeV below BB.
  - Resonance $0(1^+)$ 5 MeV below $B^* B^*$
  - Higher resonances

Estimate of the lifetime of T_{bb}

- Unlike charm, beauty decays with an almost constant lifetime
- $\tau(B^{\pm}) \sim \tau(B^0) \sim \tau(B_s) \sim \tau(\Lambda_b) \sim 1.5\,\mathrm{ps}$
- More delicate $\tau(B_c) \sim 0.5\,\mathrm{ps}$
- One could naively expect $\tau(T_{bb}) \sim 1.5\,\mathrm{ps}$
- Faster? Two b quarks
- Longer τ?
  - Average PS for $T \to B + c + X$ less than for $B \to c + X$
  - After W emission, $c\bar{q}$ not always color singlet
- KR estimated $\tau \sim 0.4\,\mathrm{ps}$
- Ali et al. $\tau \sim 0.8\,\mathrm{ps}$
- Hernandez et al. $\tau \sim 7.6\,\mathrm{ps}$
- See, also, Xing & Zhu: many “gold” channels identified

Semi-leptonic modes

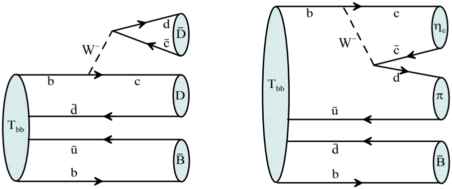




Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$\bar{B}^{*0}\; e^-\; \bar{\nu}_e$	0.0365 ± 0.0004
$\bar{B}^0\; e^-\; \bar{\nu}_e$	0.0394 ± 0.0006
$\bar{B}^{*0}\; \mu^-\; \bar{\nu}_\mu$	0.0355 ± 0.0004
$\bar{B}^0\; \mu^-\; \bar{\nu}_\mu$	0.0396 ± 0.0006
$\bar{B}^{*0}\; \tau^-\; \bar{\nu}_\tau$	0.0355 ± 0.0004
$\bar{B}^0\; \tau^-\; \bar{\nu}_\tau$	0.0396 ± 0.0006

Final state	Γ [10^{-15} GeV]	Final state	Γ [10^{-15} GeV]
$B^{*-}\, D^{*+}\, \ell^-\, \bar\nu_\ell$ $\bar B^{*0}\, D^{*0}\, \ell^-\, \bar\nu_\ell$	9.02 ± 0.07	$B^{*-}\, D^{*+}\, \tau^-\, \bar\nu_\tau$ $\bar B^{*0}\, D^{*0}\, \tau^-\, \bar\nu_\tau$	1.55 ± 0.01
$B^{*-}\, D^{+}\, \ell^-\, \bar\nu_\ell$ $\bar B^{*0}\, D^{0}\, \ell^-\, \bar\nu_\ell$	3.59 ± 0.03	$B^{*-}\, D^{+}\, \tau^-\, \bar\nu_\tau$ $\bar B^{*0}\, D^{0}\, \tau^-\, \bar\nu_\tau$	0.727 ± 0.005
$B^{-}\, D^{*+}\, \ell^-\, \bar\nu_\ell$ $\bar B^{0}\, D^{*0}\, \ell^-\, \bar\nu_\ell$	4.63 ± 0.05	$B^{-}\, D^{*+}\, \tau^-\, \bar\nu_\tau$ $\bar B^{0}\, D^{*0}\, \tau^-\, \bar\nu_\tau$	0.86 ± 0.007
$B^{-}\, D^{+}\, l^-\, \bar\nu_l$ $\bar B^{0}\, D^{0}\, \ell^-\, \bar\nu_\ell$	1.92 ± 0.02	$B^{-}\, D^{+}\, \tau^-\, \bar\nu_\tau$ $\bar B^{0}\, D^{0}\, \tau^-\, \bar\nu_\tau$	0.409 ± 0.003

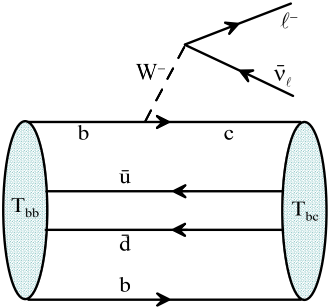
Non leptonic decays



Final state	Γ [10^{-15} GeV]	Final state	Γ [10^{-15} GeV]
$B^{*-}\ D^{*+}\ D_s^-$ $\bar{B}^{*0}\ D^{*0}\ D_s^-$	4.00 ± 0.06	$B^-\ D^{*+}\ D_s^{*-}$ $\bar{B}^0\ D^{*0}\ D_s^{*-}$	3.15 ± 0.05
$B^{*-}\ D^{*+}\ D_s^{*-}$ $\bar{B}^{*0}\ D^{*0}\ D_s^{*-}$	6.50 ± 0.09	$B^-\ D^+\ D_s^{*-}$ $\bar{B}^0\ D^0\ D_s^{*-}$	1.20 ± 0.02
$B^{*-}\ D^+\ D_s^-$ $\bar{B}^{*0}\ D^0\ D_s^-$	2.57 ± 0.04	$B^{*-}\ D^{*+}\ \rho^-$ $B^{*-}\ D^{*+}\ \pi^-$	3.57 ± 0.09 1.28 ± 0.03
$B^{*-}\ D^+\ D_s^{*-}$ $\bar{B}^{*0}\ D^0\ D_s^{*-}$	2.32 ± 0.03	$B^{*-}\ D^+\ \rho^-$ $B^{*-}\ D^+\ \pi^-$	1.70 ± 0.04 0.70 ± 0.02
$B^-\ D^{*+}\ D_s^-$ $\bar{B}^0\ D^{*0}\ D_s^-$	2.78 ± 0.05	$B^-\ D^{*+}\ \rho^-$ $B^-\ D^{*+}\ \pi^-$	2.01 ± 0.05 0.77 ± 0.03

$T_{bb} \to T_{bc}$ transitions

For completeness (as sometimes considered as possibly important)
Namely $T_{bb}(1^+)$ decaying with $T_{bc}(J^P = 0^+)$ in the final state.



Final state	$\Gamma\,[10^{-15}\,\mathrm{GeV}]$
$T_{bc}^0\, e^-\, \nu_e$	3.06 ± 0.03
$T_{bc}^0\, \mu^-\, \nu_\mu$	3.02 ± 0.02
$T_{bc}^0\, \tau^-\, \nu_\tau$	1.40 ± 0.01

Summary of T_{bb} decay

- Fist comprehensive study of the decay of the T_{bb}^- tetraquark beyond simple guess-by-analogy estimations.
- Total width $\Gamma \approx 87 \times 10^{-15}$ GeV,
- Lifetime $\tau \approx 7.6$ ps
- The promising final states are, for SL
  - $\bar{B}^{*-}\, D^{*+}\, l^-\, \bar{\nu}_\ell$
  - $\bar{B}^{*0}\, D^{*0}\, \ell^-\, \bar{\nu}_\ell$
- and, for NL
  - $\bar{B}^{*-}\, D^{*+}\, D_s^{*-}$,
  - $\bar{B}^{*0}\, D^{*0}\, D_s^{*-}$,
  - $B^{*-}\, D^{*+}\, \rho^-$
- SL mode $T_{bc}^0\, \ell^- \nu_\ell$ relevant but not dominant
- Hopefully will help for experimental tracking
- Some rare but trigger-friendly modes: $J/\psi BK$ or baryon-antibaryon stressed in the literature

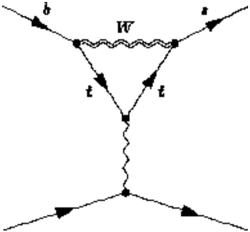
Overall summary

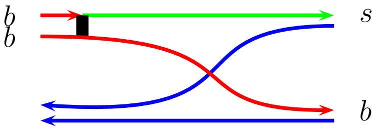
- At the quark level, triumph of chromoelectricity
- Striking analogy with atomic physics H_2 vs. Ps_2
- Possibility of excited bound states or resonances near $B^{(*)}\,B^{(*)}$
- New chapter of weak interactions
- $\tau(bb\bar{u}\bar{d}) > \tau(bbq)$ might help identification

EXTRA SLIDES

Some rare but interesting channels

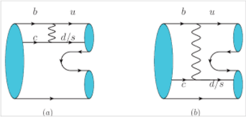
$T_{bb} \to \bar{B}\bar{K}$ via penguin?

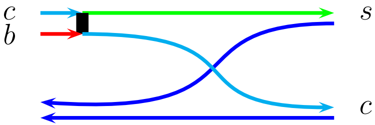




Some rare but interesting channels

$T_{bc} \to D\bar{K}$ via W-exchange?





See, e.g., T. Gershon & A. Poluektov