Doubly heavy baryons

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Double heavy baryons from the theoretical point of view

- Consisted from two heavy quarks and one light quark: $(Q_1 Q_2 q)$.
- Several scales are in game:

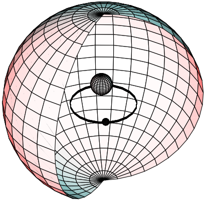
$$m_Q \gg m_{Q_1} \cdot v, m_{Q_2} \cdot v \gg m_{Q_1} v^2, m_{Q_2} v^2 \gg \Lambda_{\rm QCD}$$

(v.s. $m_Q \gg \Lambda_{\rm QCD}$ for heavy baryons).

- In the limit $m_Q \to \infty$, the light quark sees the heavy diquark as a local heavy source of a gluon field.
- Two-step calculation are possible: $\boxed{\text{diquark in } \bar{3}_c} + \boxed{\text{quark-diquark system}}$.
- The total spin of the diquark is a good quantum number within this approach.

The alternative way: the solving of three-body problem [Albertus et al., 2007a, Albertus et al., 2007b].

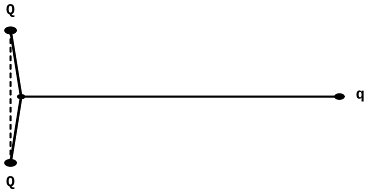
Scales for Ξ_{bc}:



The character of strong interactions in the doubly heavy baryon Ξ_{bc}: the compton lengths of quarks $\lambda_Q = 1/m_Q$, the size of heavy diquark $r_{bc} \sim 1/(v \cdot m_Q)$ and the scale of nonperturbative confinement of light quark $r_{QCD} = 1/\Lambda_{QCD}$ are arranged by $\lambda_b \approx \frac{1}{3}\,\lambda_c \approx \frac{1}{9}\,r_{bc} \approx \frac{1}{27}\,r_{QCD}$ [Kiselev and Likhoded, 2002a].

Spectroscopy

We assume that light quark interact with the heavy diquark (and not with heavy quarks separately):



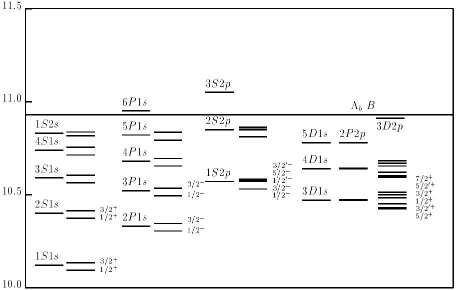
To obtain the spectrum of family of doubly heavy baryons we need:

- to obtain the spectrum of diquark by analogy with heavy quarkonium.
- for diquark consisted from equivalent quarks choose the anti-symmetric wave functions.
- to obtain the spectrum of diquark - light quark system by analogy with heavy-light meson.
- to estimate the mixing between states with the same quantum numbers.

The quark identity simplifies the spectrum:

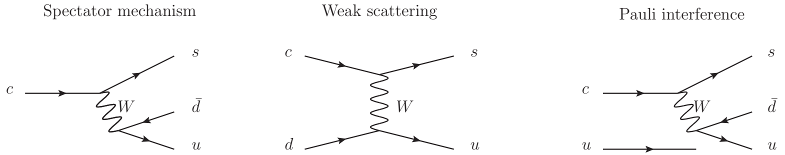
- S-wave and D-wave state of QQ diquark: $S_{QQ} = 1$
- P-wave state: $S_{QQ} = 0$

The spectrum of Ξ_{bb} [Gershtein et al., 1999]:



See also [Flynn et al., 2003, Brambilla et al., 2005].

Double heavy baryons decays



The spectator mechanism does not work.

Mode or decay mechanism	Width, ps^{-1}	Contribution,% (Ξ_{cc}^{++})	Contribution,% (Ξ_{cc}^{+})
$c \to s\bar{d}u$	2.648	127	31
$c \to se^{+}\nu$	0.380	18	4.2
PI	-1.317	-63	–
WS	5.254	–	60.6
$\Gamma_{\Xi_{cc}^{++}}$	2.089	100	–
$\Gamma_{\Xi_{cc}^{+}}$	8.660	–	100

Why lifetimes are very important

Table : The lifetimes of doubly heavy baryons [Kiselev and Likhoded, 2002a, Kiselev et al., 2000, Kiselev et al., 1999].

baryon	τ, ps	baryon	τ, ps	baryon	τ, ps
Ξ_{cc}^{++}	0.46 ± 0.05	Ξ_{bc}^{+}	0.30 ± 0.04	Ξ_{bb}^{0}	0.79 ± 0.02
Ξ_{cc}^{+}	0.16 ± 0.05	Ξ_{bc}^{0}	0.27 ± 0.03	Ξ_{bb}^{-}	0.80 ± 0.02
Ω_{cc}^{+}	0.27 ± 0.06	Ω_{bc}^{0}	0.22 ± 0.04	Ω_{bb}^{-}	0.80 ± 0.02

The strong splitting of lifetimes contributions of nonspectator terms, especially in the presence of charmed quark:

$$\begin{aligned} \tau[\Xi_{cc}^{++}] &> \tau[\Omega_{cc}^{+}] > \tau[\Xi_{cc}^{+}], \\ \tau[\Xi_{bc}^{+}] &> \tau[\Xi_{bc}^{0}] > \tau[\Omega_{bc}^{0}], \\ \tau[\Xi_{bb}^{-}] &\approx \tau[\Omega_{bb}^{-}] > \tau[\Xi_{bb}^{0}]. \end{aligned}$$

The measurements of doubly heavy baryons would be the crucial test of the OPE approach.

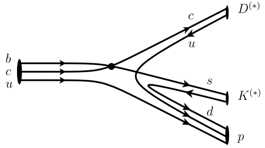
Examples of exclusive decays

Estimation within SR [Gershtein et al., 1999]

Mode	Br (%)	Mode	Br (%)
$\Xi_{bb}^{\diamond} \to \Xi_{bc}^{\diamond} l\bar{\nu}_l$	14.9	$\Xi_{bc}^{+} \to \Xi_{cc}^{++} l\bar{\nu}_l$	4.9
$\Xi_{bc}^{0} \to \Xi_{cc}^{+} l\bar{\nu}_l$	4.6	$\Xi_{bc}^{+} \to \Xi_{b}^{0} \bar{l}\nu_l$	4.4
$\Xi_{bc}^{0} \to \Xi_{b}^{-} \bar{l}\nu_l$	4.1	$\Xi_{cc}^{++} \to \Xi_{c}^{+} \bar{l}\nu_l$	16.8
$\Xi_{cc}^{+} \to \Xi_{c}^{0} \bar{l}\nu_l$	7.5	$\Xi_{bb}^{\diamond} \to \Xi_{bc}^{\diamond} \pi^{-}$	2.2
$\Xi_{bb}^{\diamond} \to \Xi_{bc}^{\diamond} \rho^{-}$	5.7	$\Xi_{bc}^{+} \to \Xi_{cc}^{++} \pi^{-}$	0.7
$\Xi_{bc}^{0} \to \Xi_{cc}^{+} \pi^{-}$	0.7	$\Xi_{bc}^{+} \to \Xi_{cc}^{++} \rho^{-}$	1.9
$\Xi_{bc}^{0} \to \Xi_{cc}^{+} \rho^{-}$	1.7	$\Xi_{bc}^{+} \to \Xi_{b}^{0} \pi^{+}$	7.7
$\Xi_{bc}^{0} \to \Xi_{b}^{-} \pi^{+}$	7.1	$\Xi_{bc}^{+} \to \Xi_{b}^{0} \rho^{+}$	21.7
$\Xi_{bc}^{0} \to \Xi_{b}^{-} \rho^{+}$	20.1	$\Xi_{cc}^{++} \to \Xi_{c}^{+} \pi^{+}$	15.7
$\Xi_{cc}^{+} \to \Xi_{c}^{0} \pi^{+}$	11.2	$\Xi_{cc}^{++} \to \Xi_{c}^{+} \rho^{+}$	46.8
$\Xi_{cc}^{+} \to \Xi_{c}^{0} \rho^{+}$	33.6		

This decay could be observed:

$$\Xi_{bc} \to D^{(*)} K^{(*)} p \ (Br \sim 0.1\%)$$



More better than
$\Xi_{bc} \to \Xi_{cc} + X \to \Xi_c + X \to \Xi + X.$

It is very difficult to find the "golden decay mode" for doubly heavy baryons.

How to produce doubly heavy baryons

Two steps:

- To produce doubly heavy diquark in a hard process in the color triplet state.
- To transform it into the baryon.

The strategy is analogous to the used one for estimation of J/ψ or B_c production cross section:

$$(Q_1\bar{Q}_2)_{1_c} \Rightarrow [Q_1Q_2]_{\bar{3}_c}$$

$$|R_{1_c}(0)|^2 \Rightarrow |R_{\bar{3}_c}(0)|^2$$

Quarks in $\bar{3}_c$ attract each other and

$$|R(0)^{Q_1Q_2}_{\bar{3}_c}|^2 \approx \frac{|R(0)^{Q_1\bar{Q}_2}_{1_c}|^2}{4}$$

Some research groups also use $[QQ]_{6_c}$ as a baryon pattern. Seems, not good idea, because quarks in 6_c repulse each other.

$[QQ]_{\bar{3}_c}$ looks like a "heavy antiquark", and therefore we could try to use a fragmentation model to transform it to the doubly heavy baryon:

$$[QQ]_{\bar{3}_c}(\vec{p}) \xrightarrow{D(z)dz} H(z\vec{p})$$

Several important problems:

- Why $[Q_1Q_2]\bar{3}_c$ do not dissociate to mesons?
- What is the probability value for $(QQ)_{\bar{3}_c}$ to create the doubly heavy baryon?
- What is the shape of fragmentation function $[Q_1Q_2]_{\bar{3}_c} \to (Q_1Q_2q)$?

bc-diquark production amplitude

$$A^{SJj_z} = \int T^{Ss_z}_{b\bar{b}c\bar{c}}(p_i, k(\vec{q})) \cdot \left(\Psi^{Ll_z}_{[bc]_{\bar{3}_c}}(\vec{q})\right)^* \cdot C^{Jj_z}_{s_z l_z} \frac{d^3\vec{q}}{(2\pi)^3},$$

where $T^{Ss_z}_{b\bar{b}c\bar{c}}$ is an amplitude of the hard production of two heavy quark pairs;
$\Psi^{Ll_z}_{\bar{b}c}$ is the diqaurk wave function (color antitriplet);
J and j_z are the total angular momentum and its projection on z-axis in the $[bc]_{\bar{3}_c}$ rest frame;
L and l_z are the orbital angular momentum of bc-diqaurk and its projection on z-axis;
S and s_z are bc-diquark spin and its projection;
$C^{Jj_z}_{s_z l_z}$ are Clebsh-Gordon coefficients;
p_i are four momenta of diquark, $\bar{b}$ quark and $\bar{c}$ quark;
$\vec{q}$ is three momentum of b-quark in the bc-diquark rest frame (in this frame $(0, \vec{q}) = k(\vec{q})$).
Under assumption of small dependence of $T^{Ss_z}_{b\bar{b}c\bar{c}}$ on $k(\vec{q})$

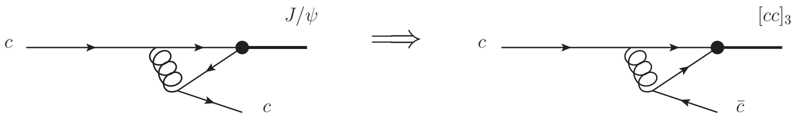
$$A \sim \int d^3q\, \Psi^*(\vec{q}) \left\{ T(p_i, \vec{q})|_{\vec{q}=0} + \vec{q}\frac{\partial}{\partial\vec{q}} T(p_i, \vec{q})|_{\vec{q}=0} + \cdots \right\}$$

and, particularly, for the S-wave states

$$A \sim R_S(0) \cdot T_{b\bar{b}c\bar{c}}(p_i)|_{\vec{q}=0},$$

where $R_S(0)$ is a value of radial wave function at origin.

Fragmentation to diquark



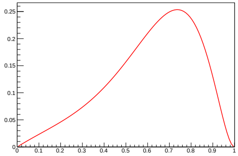
For e^+e^--annihilation at $4m_c^2/s \ll 1$ the fragmentation model can be applied:

$$Q(\vec{p}) \xrightarrow{D(z)dz} [QQ]_{\bar{3}_c}(z\vec{p})$$

$$D_{c\to cc}(z) = \frac{2}{9\pi}\,\frac{|R_{cc}(0)|^2}{m_c^3}\times$$
$$\times\,\alpha_s^2(4m_c^2)\,\frac{z(1-z)^2}{(2-z)^6}\,(16-32z+72z^2-32z^3+5z^4),$$

An absolute analog of the fragmentation function for $c \to J/\psi + c$. [Falk et al., 1994]

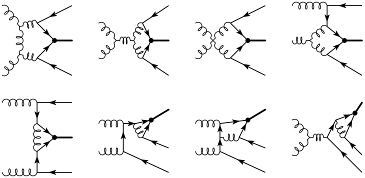
$D_{c\to cc}(z)$ has a common "Peterson-like" shape:



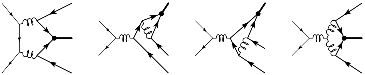
diquark production in the hadronic interaction

Many non-fragmentational diagrams contribute to the hadronic production:

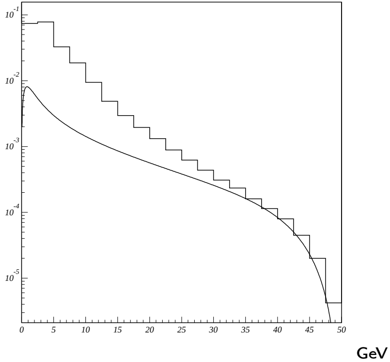
$gg \to (cc)_{\bar{3}} + X$



$q\bar{q} \to (cc)_{\bar{3}} + X$



$d\sigma(gg \to [cc]_{\bar{3}_c} + X)/dp_T$, $\sqrt{s_{gg}} = 100$ GeV, pb/GeV



Histogram: full set of diagrams
Curve: fragmentation approach

From diquark to baryon

Diquark production ($k \sim 0.2 \div 0.3$):

- $\sigma([bc]_{\bar{3}_c}) \sim k \cdot \sigma(B_c)$
- $\sigma([cc]_{\bar{3}_c}) \sim k \cdot \sigma^{\mathrm{SPS}}(J/\psi + c)$
- $\sigma([bb]_{\bar{3}_c}) \sim k \cdot \sigma^{\mathrm{SPS}}(\Upsilon + b)$
- Seems, DPS does not contribute to the double heavy diquark production.

The Peterson-like FF can used to simulate the transformation of diquark to baryon [Peterson et al., 1983]:

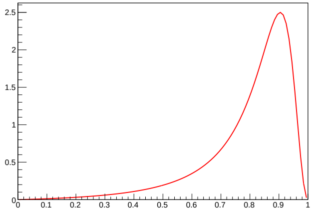
$$D(z) \sim \frac{1}{z} \frac{1}{(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2},$$

where $\epsilon \sim \frac{m_q^2}{M_{QQ}^2}$, $m_q \sim \Lambda_{\mathrm{QCD}}$

The normalization is unknown:

$$P([QQ]_{\bar{3}_c} \to \Xi_{QQ}) \leq 1$$

Quite sharp even for Ξ_{cc}:



What we could expect:

- $\sigma(\Xi_{QQ}) \lesssim 0.3 \cdot \sigma^{\mathrm{SPS}}((Q\bar{Q}) + Q)$.
- $\sigma(\Xi_{bc}) \lesssim 0.3 \cdot \sigma(B_c)$.
- p_T-distribution for Ξ_{bc} softer than for B_c-meson.

[Baranov, 1997, Berezhnoy et al., 1996, Berezhnoy et al., 1998, Chang et al., 2006, Chang et al., 2007, Zhang et al., 2011, Chen et al., 2014]

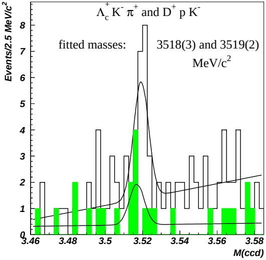
SELEX results

Peak interpreted as Ξ_{cc}^+ is seen at fixed target experiment SELEX for baryon beams only(Σ^- and p, not π^-) in modes $\Xi_{cc}^+ \to \Lambda_c K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ [Ocherashvili et al., 2005].

$$\frac{\Gamma(pD^+K^-)}{\Gamma(\Lambda_c K^- \pi^+)} = 0.36 \pm 0.21 \qquad \tau(\Xi_{cc}^+) < 0.033 \text{ ps}$$

$$N(\Xi_{cc}^+)/N(\Lambda_c) \approx 20\%$$

No confirmation from other experiments.



The predicted lifetime is

$$\tau[\Xi_{cc}^+] = 0.16 \pm 0.05 \text{ ps},$$

The extremely short lifetime would point to the unexpected breaking of OPE in the doubly heavy baryons.

Extremely high production rate also unexpected.
Very optimistic estimation:

$$\left[\frac{\sigma(c\bar{c}c\bar{c})}{\sigma(c\bar{c})}\right]^{\text{SELEX}} < \left[\frac{\sigma(c\bar{c}c\bar{c})}{\sigma(c\bar{c})}\right]^{\text{LHCb}} \times 10^{-2}(\text{threshold}) \sim 10^{-3}$$

$\sigma(\Xi_{cc})/\sigma(c\bar{c}c\bar{c}) < 0.1$ (also very optimistic)

$$\sigma(\Lambda_c)/\sigma(c\bar{c}) \approx 0.07$$

$$\boxed{\sigma(\Xi_{cc})/\sigma(\Lambda_c) \lesssim 10^{-3}}$$

The fist where these problems had been discussed in [Kiselev and Likhoded, 2002b].

Ξ_{cc}: SELEX v.s. LHCb

Recent estimation within the intrinsic charm model gives $\sigma(\Xi_{cc})/\sigma(\Lambda_c) \sim 10^{-2}$ [Koshkarev, 2014].
10^{-2} is better than 10^{-3}, but it does not solve the problem (we need 0.2 as minimum).

$$Br(\Xi_{cc} \to \Lambda_c K^- \pi^+) + Br(\Xi_{cc} \to p D^+ K^-) < 1$$

For comparison:

$$Br(\Lambda_c) \to p K^- \pi^+) \sim 5\%$$

The resonance observed by SELEX and interpreted as Ξ_{cc} have an extremely short lifetime and an extremely large cross-section.

Doubly charmed baryon from SELEX would mean:

- strong breaking of OPE;
- new mechanism of charm production (not IC, not DPS, not k_T-factorization).

LHCb results for 0.65 fb^{-1} at $\sqrt{s} = 7$ TeV [Aaij et al., 2013]:
from $R < 1.5 \times 10^{-2}$ for a lifetime of 100 fs to $R < 3.9 \times 10^{-4}$ for a lifetime of 400 fs (at 95% CL), where

$$R = \frac{\sigma(\Xi_{cc}) Br(\Xi_{cc} \to \Lambda_c K^- \pi^+)}{\sigma(\Lambda_c)}$$

Should be compared with $R \sim 9\%$ at SELEX.
The predicted value of R is about $10^{-5} \div 10^{-4}$.

Ξ_{cc} at LHCb

Table : Expected value of the signal yield in LHCb, assuming $m(\Xi_{cc}^{+}) = 3500$ MeV/c^2.

τ	$R = 9\%$	$R = 10^{-4}$	$R = 10^{-5}$
100 fs	140 $\pm$ 70	0.2 $\pm$ 0.1	0.02 $\pm$ 0.01
150 fs	600 $\pm$ 200	0.7 $\pm$ 0.2	0.07 $\pm$ 0.02
250 fs	2200 $\pm$ 600	2.4 $\pm$ 0.7	0.24 $\pm$ 0.07
333 fs	3600 $\pm$ 900	4.0 $\pm$ 1.0	0.40 $\pm$ 0.10
400 fs	4800 $\pm$ 1200	5.3 $\pm$ 1.4	0.53 $\pm$ 0.14

Table : Largest values of UL on R at the 95% CL ($M(\Xi_{cc}) = 3000$ MeV/$c^2 + \delta m$).

	R, largest 95% CL UL in range $\times 10^{-3}$				
δm (MeV/c^2)	100 fs	150 fs	250 fs	333 fs	400 fs
380–429	12.6	2.7	0.73	0.43	0.33
430–479	11.2	2.4	0.65	0.39	0.29
480–529	14.8	3.2	0.85	0.51	0.39
530–579	10.7	2.3	0.63	0.38	0.29
580–629	10.9	2.3	0.63	0.38	0.29
630–679	14.2	3.0	0.81	0.49	0.37
680–729	9.5	2.0	0.56	0.33	0.25
730–779	10.8	2.3	0.63	0.37	0.28
780–829	12.8	2.8	0.74	0.45	0.34
830–880	12.2	2.6	0.70	0.42	0.32
380–880	14.8	3.2	0.85	0.51	0.39

Conclusions

- The lifetime measurements of doubly heavy baryons would be the crucial test of the OPE approach.
- The research of doubly heavy baryon production would allow to answer how often a diquark transform to the baryon.
- DPS does not contribute to the double heavy diquark production. Very interesting to compare $\sigma(\Xi_{bc})/\sigma(B_c)$, $\sigma(\Xi_{cc})/\sigma(J/\psi + c)$ and $\sigma(\Xi_{bb})/\sigma(\Upsilon + b)$.
- May be it worth to think about Ξ_{cc}^{++} (~ 0.46 ps) in addition to Ξ_{cc}^{+} (~ 0.16 ps).
- The most optimistic estimations:
  - $\sigma(\Xi_{QQ}) \lesssim 0.3 \cdot \sigma^{\mathrm{SPS}}((Q\bar{Q}) + Q)$.
  - $\sigma(\Xi_{bc}) \lesssim 0.3 \cdot \sigma(B_c)$.
- p_T-distribution for Ξ_{bc} softer than for B_c-meson.
- It is worth to try mode DKp both for Ξ_{cc} and Ξ_{bc}.
- It is very difficult to find the "golden decay mode" for doubly heavy baryons.

Many thanks for your attention.

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