Double heavy baryons from the theoretical point of view

Workshop on Heavy Baryons at LHCb, CERN

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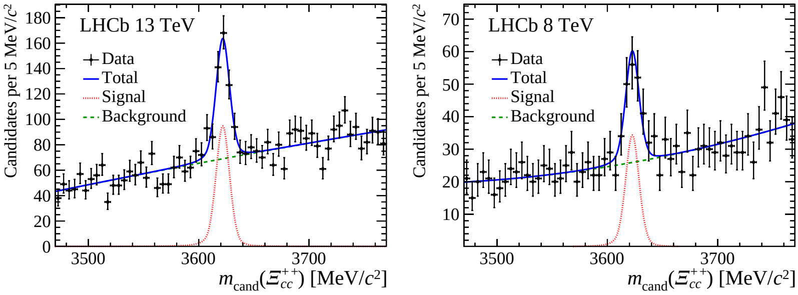
Congratulations

Our congratulations to the LHCb Collaboration on the observation of doubly charmed baryon!!!



$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

[Aaij et al., 2017b]

Contents

- Introduction.
- Spectroscopy of DHB.
- Weak decays of DHB.
- Production.

Very short introduction into double heavy baryons

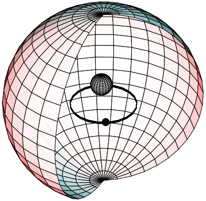
- Consisted from two heavy quarks and one light quark: $(Q_1 Q_2 q)$.
- Several scales are in game:

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

  (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] and much earlier work [Kerbikov et al., 1990].

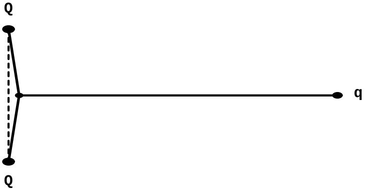
Scales for Ξ_{bc}:



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, 2002].

Spectroscopy

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



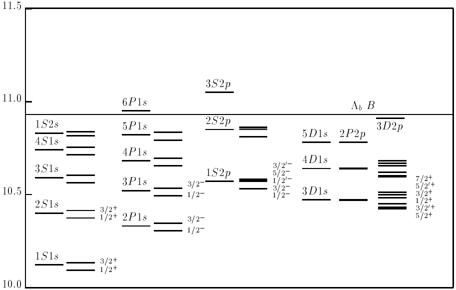
To obtain the spectrum of family of doubly heavy baryons we need:

- to obtain the spectrum of the diquark by analogy with the 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 the 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., 1999a]:



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

Ξ_{cc}^{++} and Ξ_{cc}^{+} mass spectra

$(n_d L_d n_l L_l)$, J^P	mass, GeV	$(n_d L_d n_l L_l)$, J^P	mass, GeV
(1S 1s)$1/2^+$	3.478	(3P 1s)$1/2^-$	3.972
(1S 1s)$3/2^+$	3.61	(3D 1s)$3/2'^+$	4.007
(2P 1s)$1/2^-$	3.702	(1S 2p)$3/2'^-$	4.034
(3D 1s)$5/2^+$	3.781	(1S 2p)$3/2^-$	4.039
(2S 1s)$1/2^+$	3.812	(1S 2p)$5/2^-$	4.047
(3D 1s)$3/2^+$	3.83	(3D 1s)$5/2'^+$	4.05
(2P 1s)$3/2^-$	3.834	(1S 2p)$1/2'^-$	4.052
(3D 1s)$1/2^+$	3.875	(3S 1s)$1/2^+$	4.072
(1S 2p)$1/2^-$	3.927	(3D 1s)$7/2^+$	4.089
(2S 1s)$3/2^+$	3.944	(3P 1s)$3/2^-$	4.104

Ξ_{cc}(2P 1s) is metastable, because transition to the ground state requires the angular momentum and the total spin diquark to change simultaneously. So, maybe it is worth to pay attention to the decay Ξ_{cc}^{+}(2P 1s) $\to \Xi_{cc}^{++}\pi^-$.

Mass corrections due to diquark finite size

Taking into account the heavy diquark size increases the baryon masses.

Within the local-diquark approximation

$$m[\Xi_{cc}^{1/2^{++}}] \approx m[\Xi_{cc}^{1/2^{+}}] = 3478 \pm 30 \text{ MeV},$$

and

$$m[\Xi_{cc}^{3/2^{++}}] \approx m[\Xi_{cc}^{3/2^{+}}] = 3610 \pm 30 \text{ MeV}.$$

However, the actual sizes of doubly charmed diquarks are not negligible. As we have found in [Gershtein et al., 2000, Gershtein et al., 1999b], the sizes of basic vector $1S$-diquarks:

$$\langle r^2 \rangle_{cc}^{/2} = 0.58 \text{ fm}$$

$$\langle r^2 \rangle_{bb}^{/2} = 0.33 \text{ fm}$$

Accounting of diquark size within two different approaches increases the mass values:

- form factor: $\delta M(\Xi_{cc}) \approx 80$ MeV [Ebert et al., 2002];
- longer string inside non-local diquark: $\delta M(\Xi_{cc}) \approx 80$ MeV [Kiselev et al., 2017].

Therefore:

$$m[\Xi_{cc}^{1/2^{++}}] \approx m[\Xi_{cc}^{1/2^{+}}] = 3615 \pm 55 \text{ MeV},$$

$$m[\Xi_{cc}^{3/2^{++}}] \approx m[\Xi_{cc}^{3/2^{+}}] = 3747 \pm 55 \text{ MeV}.$$

Taking into account the diquark form factor

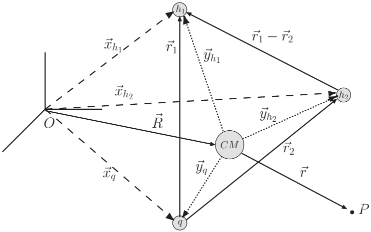
Mass spectrum of Ξ_{cc} baryons in GeV.

State	Mass		State	Mass	
$(n_d L n_q l) J^P$	EFGM	our	$(n_d L n_q l) J^P$	EFGM	our
$(1S1s)1/2^+$	3.620	3.478	$(1P1s)1/2^-$	3.838	3.702
$(1S1s)3/2^+$	3.727	3.61	$(1P1s)3/2^-$	3.959	3.834
$(1S1p)1/2^-$	4.053	3.927	$(2S1s)1/2^+$	3.910	3.812
$(1S1p)3/2^-$	4.101	4.039	$(2S1s)3/2^+$	4.027	3.944
$(1S1p)1/2'^-$	4.136	4.052	$(2P1s)1/2^-$	4.085	3.972
$(1S1p)5/2^-$	4.155	4.047	$(2P1s)3/2^-$	4.197	4.104
$(1S1p)3/2'^-$	4.196	4.034	$(3S1s)1/2^+$	4.154	4.072

EFGM: D. Ebert, R. N. Faustov, V. O. Galkin, A. P. Martynenko [Ebert et al., 2002]

Alternative way: to solve the three-body problem

C. Albertus, E. Hernandez, J. Nieves, J.M. Verde-Velasco [Albertus et al., 2007a, Albertus et al., 2007b]



Masses of ground states in GeV

Ξ_{cc}	3612^{+17}
Ξ^*_{cc}	3706^{+23}
Ξ_{bb}	10197^{+10}_{-17}
Ξ^*_{bb}	10236^{+9}_{-17}
Ξ_{bc}	6919^{+17}_{-7}
Ξ'_{bc}	6948^{+17}_{-6}
Ξ^*_{bc}	6986^{+14}_{-5}

Much earlier work of B. Kerbikov, M. Polikarpov and L. Shevchenko [Kerbikov et al., 1990]

Masses of centers of gravity $M_{c.o.g.}$ and the expectation values δ_{ij} and $\langle r_{ij}^2\rangle^{1/2}$ for baryons

System	$M_{c.o.g.}$ (MeV)	$10^3\ \delta_{ij}$ (GeV^3)	$\langle r_{ij}^2\rangle^{1/2}$ (GeV^{-1})
udu	1087.8 ± 0.3	$\delta_{12} = \delta_{13} = \delta_{23} = 4.98 \pm 0.61$	$\langle r_{12}^2\rangle^{1/2} = \langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 4.480 \pm 0.009$
uds	1271.7 ± 0.4	$\delta_{12} = 4.07 \pm 0.41$; $\delta_{13} = \delta_{23} = 6.85 \pm 0.72$	$\langle r_{12}^2\rangle^{1/2} = 4.421 \pm 0.014$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 4.087 \pm 0.019$
udc	2413.9 ± 1.3	$\delta_{12} = 5.24 \pm 0.85$; $\delta_{13} = \delta_{23} = 8.51 \pm 1.10$	$\langle r_{12}^2\rangle^{1/2} = 4.295 \pm 0.024$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 3.631 \pm 0.037$
udb	5768.7 ± 2.0	$\delta_{12} = 5.21 \pm 1.03$; $\delta_{13} = \delta_{23} = 12.22 \pm 1.21$	$\langle r_{12}^2\rangle^{1/2} = 4.269 \pm 0.042$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 3.461 \pm 0.039$
usc	2562.2 ± 1.7	$\delta_{12} = 7.49 \pm 1.08$; $\delta_{13} = 9.87 \pm 1.44$; $\delta_{23} = 17.99 \pm 1.99$	$\langle r_{12}^2\rangle^{1/2} = 3.935 \pm 0.036$; $\langle r_{13}^2\rangle^{1/2} = 3.582 \pm 0.021$; $\langle r_{23}^2\rangle^{1/2} = 3.072 \pm 0.021$
sss	1604.9 ± 1.3	$\delta_{12} = \delta_{13} = \delta_{23} = 9.91 \pm 0.89$	$\langle r_{12}^2\rangle^{1/2} = \langle r_{13}^2\rangle^{1/2}$; $\langle r_{23}^2\rangle^{1/2} = 3.557 \pm 0.026$
ssu	1444.9 ± 0.7	$\delta_{12} = 9.97 \pm 0.85$; $\delta_{13} = \delta_{23} = 6.34 \pm 0.80$	$\langle r_{12}^2\rangle^{1/2} = 3.587 \pm 0.020$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 3.996 \pm 0.033$
ssc	2704.8 ± 1.8	$\delta_{12} = 10.88 \pm 1.28$; $\delta_{13} = \delta_{23} = 17.66 \pm 1.61$	$\langle r_{12}^2\rangle^{1/2} = 3.458 \pm 0.033$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.996 \pm 0.030$
ssb	6040.9 ± 2.4	$\delta_{12} = 11.51 \pm 1.58$; $\delta_{13} = \delta_{23} = 24.16 \pm 2.40$	$\langle r_{12}^2\rangle^{1/2} = 3.367 \pm 0.020$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.770 \pm 0.026$
ccc	4776.1 ± 6.2	$\delta_{12} = \delta_{13} = \delta_{23} = 63.47 \pm 8.60$	$\langle r_{12}^2\rangle^{1/2} = \langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.118 \pm 0.034$
V ccu	3632.8 ± 2.4	$\delta_{12} = 45.25 \pm 2.90$; $\delta_{13} = \delta_{23} = 11.28 \pm 1.94$	$\langle r_{12}^2\rangle = 2.322 \pm 0.024$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 3.407 \pm 0.035$
ccs	3760.7 ± 2.4	$\delta_{12} = 50.30 \pm 2.53$; $\delta_{13} = \delta_{23} = 18.63 \pm 1.22$	$\langle r_{12}^2\rangle^{1/2} = 2.238 \pm 0.044$; $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.842 \pm 0.030$

Comparison of predictions for different ground states of DHB from [Albertus et al., 2007b] (I)

Reference	Ξ_{cc}	Ξ^*_{cc}	Ξ_{bb}	Ξ^*_{bb}
[Albertus et al., 2007b]	3612^{+17}	3706^{+23}	10197^{+10}_{-17}	10236^{+9}_{-17}
[Ebert et al., 2002]	3620	3727	10202	10237
[Kiselev and Likhoded, 2002]	3480	3610	10090	10130
[Narodetskii and Trusov, 2002b]	3690		10160	
[Tong et al., 2000]	3740	3860	10300	10340
[Itoh et al., 2000]	3646	3733		
[Vijande et al., 2004]	3524	3548		
[Gershtein et al., 2000]	3478	3610	10093	10133
[Ebert et al., 1997]	3660	3810	10230	10280
[Roncaglia et al., 1995a, Roncaglia et al., 1995b]	3660 ± 70	3740 ± 80	10340 ± 100	
[Korner et al., 1994]	3610	3680		
[Mathur et al., 2002]	3588 ± 72			

Comparison of predictions for different ground states of DHB from [Albertus et al., 2007b] (II)

Reference	Ξ_{bc}	Ξ'_{bc}	Ξ^*_{bc}
[Albertus et al., 2007b]	6919^{+17}_{-7}	6948^{+17}_{-6}	6986^{+14}_{-5}
[Silvestre-Brac, 1996b]	6915^{+17}_{-9}		
[Ebert et al., 2002]	6933	6963	6980
[Kiselev and Likhoded, 2002]	6820	6850	6900
[Narodetskii and Trusov, 2002b]	6960		
[Tong et al., 2000]	7010	7070	7100
[Gershtein et al., 2000]	6820	6850	6900
[Ebert et al., 1997]	6950	7000	7020
[Roncaglia et al., 1995a, Roncaglia et al., 1995b]	6965 ± 90	7065 ± 90	7060 ± 90
[Mathur et al., 2002]	6840 ± 236		

Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (I)

Reference	Value (MeV)	Method
[Karliner and Rosner, 2014]	3627 ± 12	
[De Rujula et al., 1975]	$3550 - 3760$	QCD-motivated quark model
J. Bjorken (unpublished draft, 1986)	3668 ± 62	QCD-motivated quark model
[Anikeev et al., 2001]	3651	QCD-motivated quark model
[Fleck and Richard, 1989]	3613	Potential and bag models
[Richard, 1994]	3630	Potential model
[Korner et al., 1994]	3610	Heavy quark effective theory
[Roncaglia et al., 1995b]	3660 ± 70	Feynman-Hellmann + semi-empirical
[Lichtenberg et al., 1996]	3676	Mass sum rules
[Ebert et al., 1997]	3660	Relativistic quasipotential quark model
[Silvestre-Brac, 1996a]	3607	Three-body Faddeev equations.
[Gerasyuta and Ivanov, 1999]	3527	Bootstrap quark model + Faddeev eqs.
[Itoh et al., 2000]	ucc: 3649 ± 12, dcc: 3644 ± 12	Quark model
[Kiselev and Likhoded, 2002]	3480 ± 50	Potential approach + QCD sum rules
[Narodetskii and Trusov, 2002a]	3690	Nonperturbative string
[Ebert et al., 2002]	3620	Relativistic quark-diquark

Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (II)

Reference	Value (MeV)	Method
[He et al., 2004]	3520	Bag model
[Richard and Stancu, 2005]	3643	Potential model
[Migura et al., 2006]	3642	Relativistic quark model + Bethe-Salpeter
[Albertus et al., 2007b]	3612^{+17}	Variational
[Roberts and Pervin, 2008]	3678	Quark model
[Weng et al., 2011]	3540 ± 20	Instantaneous approx. + Bethe-Salpeter
[Zhang and Huang, 2008]	4260 ± 190	QCD sum rules
[Lewis et al., 2001]	$3608(15)(^{13}_{35})$, $3595(12)(^{21}_{22})$	Quenched lattice
[Flynn et al., 2003]	$3549(13)(19)(92)$	Quenched lattice
[Liu et al., 2010]	$3665 \pm 17 \pm 14^{+0}_{-78}$	Lattice, domain-wall + KS fermions
[Namekawa, 2012]	$3603(15)(16)$	Lattice, $N_f = 2+1$
[Alexandrou et al., 2012]	$3513(23)(14)$	LGT, twisted mass ferm., m_π=260 MeV
[Briceno et al., 2012]	$3595(39)(20)(6)$	LGT, $N_f = 2+1$, $m_\pi = 200$ MeV
[Alexandrou et al., 2014]	$3568(14)(19)(1)$	LGT, $N_f = 2+1$, $m_\pi = 210$ MeV

Conclusions on spectroscopy

- Potential model heavy diquark-light quark allows to predict the DHB spectrum including high excitations.
- The corrections on finite diquark size improve an agreement with experiment.
- Three-body description with two body Cornell type potential is in an good agreement with the experiment for the ground state. However, within this model it is quite difficult to predict the masses of excited states.
- Maybe, maybe there is a more simple way to obtain the DHB spectrum (KR).

Total width within OPE

$$\Gamma_{\Xi_{cc}} = \frac{1}{2M_{\Xi_{cc}}}\langle \Xi^{\diamond}_{cc}|\mathcal{T}|\Xi^{\diamond}_{cc}\rangle$$

$$\langle \Xi_{cc}|\Xi_{cc}\rangle = 2EV$$

$$\mathcal{T} = \Im m \int d^4x \; \{\mathrm{T} H_{eff}(x) H_{eff}(0)\}$$

where H_{eff} is the standard effective hamiltonian describing the low energy weak interactions of initial quarks with the decay products. For the transition of c-quark, u-quark and the quarks $q_{1,2}$ with the charge $-1/3$, the lagrangian has the form

$$H_{eff} = \frac{G_F}{2\sqrt{2}} V_{uq_1} V^*_{cq_1} [C_+(\mu)O_+ + C_-(\mu)O_-] + \mathrm{h.c.}$$

where V is the matrix of mixing between the charged currents, and

$$O_{\pm} = [\bar{q}_{1\alpha}\gamma_\nu(1-\gamma_5)c_\beta][\bar{u}_\gamma\gamma^\nu(1-\gamma_5)q_{2\delta}](\delta_{\alpha\beta}\delta_{\gamma\delta} \pm \delta_{\alpha\delta}\delta_{\gamma\beta}),$$

α, β are color states of quarks and

$$C_+ = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{33-2n_f}}, \quad C_- = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{-12}{33-2n_f}}$$

where n_f is the number of flavors.

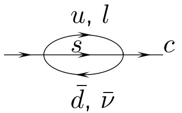
OPE for the transition operator $\mathcal{T}$

$$\mathcal{T} = C_1(\mu)\bar{c}c + \frac{1}{m_c^2}C_2(\mu)\bar{c}g\sigma_{\mu\nu}G^{\mu\nu}c + \frac{1}{m_c^3}O(1).$$

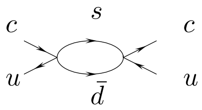
Main features:

- $\bar{c}c$ — spectator decays of c-quarks;
- no operators of dimension 4 contribute;
- the only operator of dimension 5 ;
- Pauli interference (operators of dimension 6) essentially contribute to Ξ_{cc}^{++} life time;
- weak scattering (operators of dimension 6) essentially contribute to Ξ_{cc}^{+} life time.

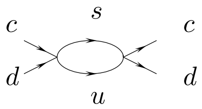
Spectator contribution:



Pauli interference:



Weak scattering:



Ξ_{cc}^{++}, Ξ_{cc}^{+} lifetimes

$$\mathcal{T}^{(\Xi_{cc}^{++})} = 2(\mathcal{T}_{35c} + \mathcal{T}^{c}_{\mathrm{PI},u\bar{d}}), \qquad \mathcal{T}^{(\Xi_{cc}^{+})} = 2(\mathcal{T}_{35c} + \mathcal{T}_{\mathrm{WS},cd}),$$

$$\mathcal{T}^{c}_{\mathrm{PI},u\bar{d}} = -\frac{G_F^2}{4\pi} m_c^2 \left(1 - \frac{m_u}{m_c}\right)^2 \times$$

$$\left\{ \left[G_1(z_-)(\bar{c}c)^{ii}_{V-A}(\bar{u}u)^{jj}_{V-A} + G_2(z_-)(\bar{c}c)^{ii}_{A}(\bar{u}u)^{jj}_{V-A} \right] \left[F_3 + \frac{1}{3}(1 - k^{\frac{1}{2}})F_4 \right] + \right.$$

$$\left. \left[G_1(z_-)(\bar{c}c)^{ij}_{V-A}(\bar{u}u)^{ji}_{V-A} + G_2(z_-)(\bar{c}c)^{ij}_{A}(\bar{u}u)^{ji}_{V-A} \right] k^{\frac{1}{2}} F_4 \right\},$$

$$\mathcal{T}_{\mathrm{WS},cd} = \frac{G_F^2}{4\pi} m_c^2 \left(1 + \frac{m_d}{m_c}\right)^2 (1 - z_+)^2 \left[(F_6 + \frac{1}{3}(1 - k^{\frac{1}{2}})F_5)(\bar{c}c)^{ii}_{V-A}(\bar{d}d)^{jj}_{V-A} + \right.$$

$$\left. k^{\frac{1}{2}} F_5 (\bar{c}c)^{ij}_{V-A}(\bar{d}d)^{ji}_{V-A} \right],$$

$$F_{1,3} = (C_+ \mp C_-)^2, \qquad F_{2,4} = 5C_+^2 + C_-^2 \pm 6C_+C_-, \quad F_{5,6} = C_+^2 \mp C_-^2,$$

$$G_1(z) = \frac{(1-z)^2}{2} - \frac{(1-z)^3}{4}, \quad G_2(z) = \frac{(1-z)^2}{2} - \frac{(1-z)^3}{3},$$

$$z_- = \frac{m_s^2}{(m_c - m_u)^2}, \qquad z_+ = \frac{m_s^2}{(m_c + m_d)^2}$$

$$(\bar{c}c)^{ii}_{V-A}(\bar{q}q)^{jj}_{V-A} = -(\bar{c}c)^{ij}_{V-A}(\bar{q}q)^{ji}_{V-A} = 12(m_c + m_q)|\Psi(0)|^2$$

Model parameters and life time estimation

$$m_c,\ m_q,\ M(\Xi_{cc}^{++}),\ M(\Xi_{cc}^{+}),\ T \text{ and } \psi_{dd}(0)$$

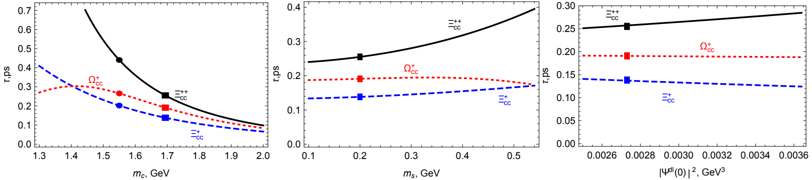
- $m_c = 1.6$ GeV — the pole c-quark mass (lifetime and semileptonic decays of D^0 meson).
- $T = 0.4$ GeV — the kinetic energy of diquark and light quark (potential models).
- $M(\Xi_{cc}^{++}) \approx M(\Xi_{cc}^{+}) \approx 3.56$ GeV – mean values (PM and SR).
- $\psi_{dd}(0) = 0.17$ GeV$^{3/2}$

$$\tau(\Xi_{cc}^{++}) = 0.48 \text{ ps} \qquad \tau(\Xi_{cc}^{+}) = 0.12 \text{ ps}$$

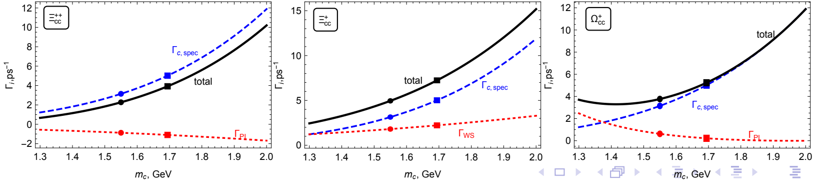
Dependence on parameter values: Ξ_{cc}, Ω_{cc}

Quarks' masses for meson and baryon could be different [Karliner and Rosner, 2014]

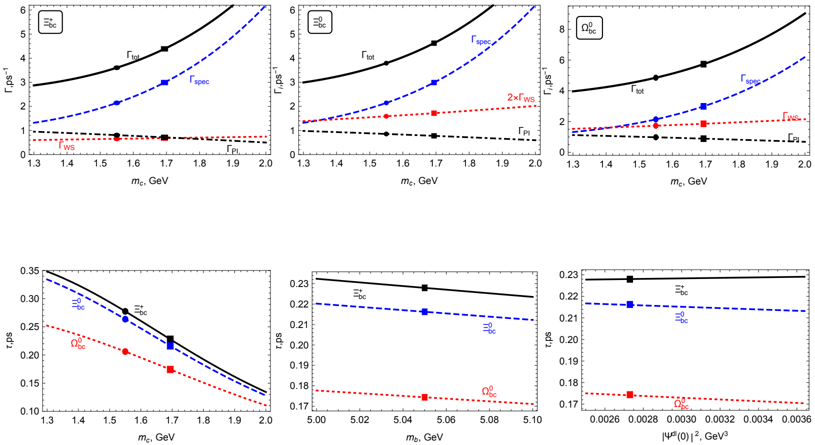
$$m_c = 1.694 \pm 0.03\,\mathrm{GeV}$$



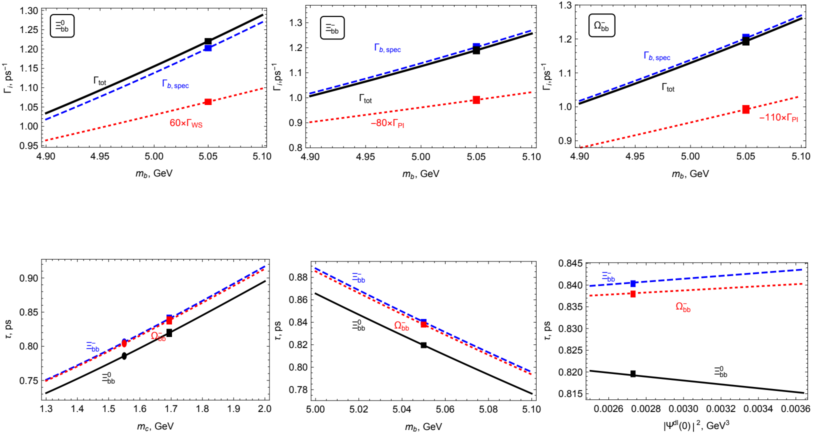
$$\tau(\Xi_{cc}^{++}) = 0.26 \pm 0.03\ \mathrm{ps}, \quad \tau(\Xi_{cc}^{+}) = 0.14 \pm 0.01\mathrm{ps}, \quad \tau(\Omega_{cc}^{+}) = 0.19 \pm 0.01\ \mathrm{ps}$$



Dependence on parameter values: Ξ_{bc}, Ω_{bc}



Dependence on parameter values: Ξ_{bb}, Ω_{bb}



Why lifetimes are very important

The contributions of different terms to the life time essentially depend on baryon composition (40-50%). From Ξ_{cc}^{++} lifetime:

$$m_c = 1.73 \pm 0.07\,\mathrm{GeV}, \qquad m_s = 0.35 \pm 0.2\,\mathrm{GeV}.$$

The lifetimes of doubly heavy baryons

baryon	τ, ps	baryon	τ, ps	baryon	τ, ps
Ξ_{cc}^{++}	0.26 ± 0.03	Ξ_{bc}^{+}	0.24 ± 0.02	Ξ_{bb}^{0}	0.52 ± 0.01
Ξ_{cc}^{+}	0.14 ± 0.01	Ξ_{bc}^{0}	0.22 ± 0.02	Ξ_{bb}^{-}	0.53 ± 0.01
Ω_{cc}^{+}	0.19 ± 0.02	Ω_{bc}^{0}	0.18 ± 0.01	Ω_{bb}^{-}	0.53 ± 0.01

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

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

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

Comparison with other Results

Karliner, Rosner // PRD 90 (2014) 094007

$$m_s = 538\,\mathrm{MeV}, \qquad m_c = 1.7105\,\mathrm{GeV}$$

$$\tau_{\Xi_{cc}^{++}} = \left[10 \frac{G_F^2 M_{\Xi_{cc}}^2}{192\pi^3} f\left(\frac{M_{\Xi_{cc}^{+}}^2}{M_{\Xi_{cc}^{++}}^2} \right) \right]^{-1} \approx 0.185\ \mathrm{ps}$$

- Do not agree with n total life
- No PI, WS $\Rightarrow \tau_{\Xi_{cc}^{+}} = \tau_{\Xi_{cc}^{++}}$

OPE $\Rightarrow \tau_{\Xi_{cc}^{++}} = 0.32\ \mathrm{ps}$

Karliner, Rosner // Phys.Rev. D97 (2018) 094006

$$m_s = 482.2\,\mathrm{MeV}, \qquad m_c = 1.6556\,\mathrm{GeV}$$

No lifetime predictions presented

OPE $\Rightarrow \tau_{\Xi_{cc}^{++}} = 0.37\ \mathrm{ps}$

Cheng, Shi // arXiv:1809.08102v1 [hep-ph]

$$m_c = 1.56\,\mathrm{GeV}$$

Dimension 7 operators

$$\tau_{\Xi_{cc}^{++}} = 0.298\,\mathrm{ps}, \qquad \tau_{\Xi_{cc}^{+}} = 0.044\,\mathrm{ps}, \qquad \tau_{\Omega_{cc}^{+}} = 0.2\mathrm{ps}$$

Exclusive decays

The formfactor of decay for the baryon with the spin $\frac{1}{2}$ into the baryon with the spin $\frac{1}{2}$ is expressed in the general form as follows:

$$\langle H_F(p_F)|J_\mu|H_I(p_I)\rangle = \bar{u}(p_F)\{\gamma_\mu G_1^V + v_\mu^I G_2^V + v_\mu^F G_3^V + \gamma_5(\gamma_\mu G_1^A + v_\mu^I G_2^A + v_\mu^F G_3^A)\}u(p_I).$$

At small recoils $v^i \sim v^f$ and $v^i \cdot v^f = w \sim 1$. This is why only two of six form factors are not suppressed by heavy qaurk mass, namely

$$G_1^V = G_1^A = \xi(w),$$

where $\xi(w)$ is so-called Isgur-Wise form factor. CVC gives $\xi(1) = 1$.

$$\xi(w) = \frac{\xi(1)}{1 - q^2/m^2_{\text{pol}}}$$

$$m_{\text{pol}}(b \to c) = 6.3 \text{ GeV}$$

$$m_{\text{pol}}(c \to s) = 1.85 \text{ GeV}$$

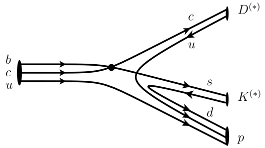
Examples of exclusive decays

Estimation within SR [Gershtein et al., 1999a]

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 $k(\vec{q})$

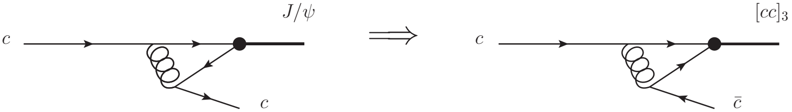
$$A \sim \int d^3q\, \Psi^*(\vec{q}) \left\{ T(p_i, \vec{q})\big|_{\vec{q}=0} + \vec{q}\frac{\partial}{\partial \vec{q}} T(p_i, \vec{q})\big|_{\vec{q}=0} + \cdots \right\}$$

and, particularly, for the S-wave states

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

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:

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

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

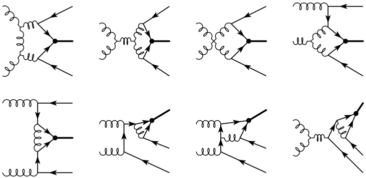
An absolute analog of the fragmentation function for $c \to J/\psi + c$. [Falk et al., 1994]

The identical quarks in the color anti-triplet state must have the symmetrical spin wave function in the S-wave, i.e. cc must be in the total spin S = 1 state.

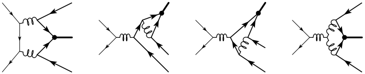
Diquark production in the hadronic interaction

Many non-fragmentational diagrams contribute to the hadronic production:

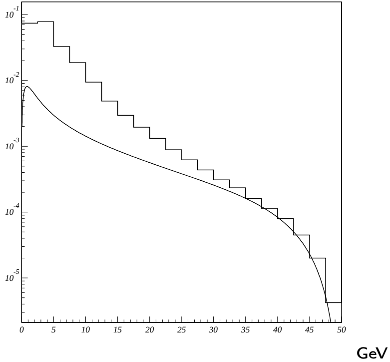
$gg \to (cc)_{\bar{3}} + X$



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



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



Histogram: full set of diagrams
Curve: fragmentation approach

Diquark ⇒ baryon

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

- $\sigma([bc]_{\bar{3}_c}) \sim k \cdot \sigma(B_c)$
- $\sigma([cc]_{\bar{3}_c}) \sim k \cdot \sigma^{\rm SPS}(J/\psi + c)$
- $\sigma([bb]_{\bar{3}_c}) \sim k \cdot \sigma^{\rm SPS}(\Upsilon + b)$
- 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]:

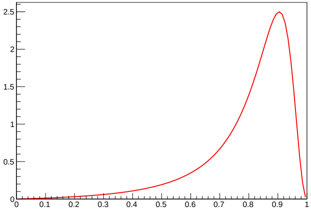
$$D(z) \sim \frac{1}{z} \frac{1}{(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2},$$

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

The normalization is unknown:

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

Quite sharp even for Ξ_{cc}:

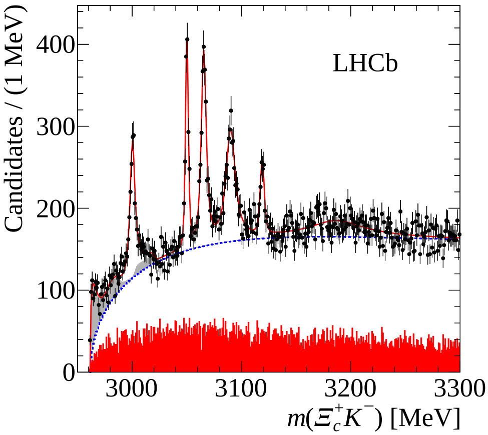


What we could expect:

- $\sigma(\Xi_{QQ}) \lesssim 0.3 \cdot \sigma^{\rm SPS}((Q\bar{Q}) + Q)$.
- $\sigma(\Xi_{bc}) \lesssim 0.3 \cdot \sigma(B_c)$.
- 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]

Five narrow Ω_s^0 states decaying to $\Xi_c^+ K^-$



[Aaij et al., 2017a]

Conclusions

- There are two main approaches to predict HDB masses: quark-diquark potential models and the three-body model with Cornell pair potentials. Both approaches successfully predicted the mass of Ξ_{cc} ground state. The quark-diquark models allow also to obtain the full particle spectrum including high excitations. Maybe the more simple way exists [KR].
- It would be very interesting to observe Ξ_{cc}^{+} and to compare the life times of Ξ_{cc}^{++} and Ξ_{cc}^{+}, because it would be the crucial test of the OPE method.
- The Ξ_{bc} production cross section should be comparable to the cross section of B_c-meson production. This is why we hope, that Ξ_{bc} baryon will also be observed at LHC.

Many thanks for your attention!

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References

Aaij, R. et al. (2017a).
Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$.
Phys. Rev. Lett., 118(18):182001.

Aaij, R. et al. (2017b).
Observation of the doubly charmed baryon Ξ_{cc}^{++}.

Albertus, C., Hernandez, E., Nieves, J., and Verde-Velasco, J. (2007a).
Doubly heavy quark baryon spectroscopy and semileptonic decay.
Eur.Phys.J., A31:691–694.

Albertus, C., Hernandez, E., Nieves, J., and Verde-Velasco, J. (2007b).
Static properties and semileptonic decays of doubly heavy baryons in a nonrelativistic quark model.
Eur.Phys.J., A32:183–199.

Alexandrou, C., Carbonell, J., Christaras, D., Drach, V., Gravina, M., and Papinutto, M. (2012).
Strange and charm baryon masses with two flavors of dynamical twisted mass fermions.
Phys. Rev., D86:114501.

Alexandrou, C., Drach, V., Jansen, K., Kallidonis, C., and Koutsou, G. (2014).
Baryon spectrum with $N_f = 2+1+1$ twisted mass fermions.
Phys. Rev., D90(7):074501.

Anikeev, K. et al. (2001).
B physics at the Tevatron: Run II and beyond.
In *Workshop on B Physics at the Tevatron: Run II and Beyond Batavia, Illinois, September 23-25, 1999*.

Baranov, S. (1997).
Hadronic and photonic production of doubly flavored baryons.
Nucl.Phys.Proc.Suppl., 55A:33–35.

Berezhnoy, A., Kiselev, V., and Likhoded, A. (1996).
Hadronic production of baryons containing two heavy quarks.
Phys.Atom.Nucl., 59:870–874.

Berezhnoy, A., Kiselev, V., Likhoded, A., and Onishchenko, A. (1998).
Doubly charmed baryon production in hadronic experiments.
Phys.Rev., D57:4385–4392.

Brambilla, N., Vairo, A., and Rosch, T. (2005).
Effective field theory Lagrangians for baryons with two and three heavy quarks.
Phys.Rev., D72:034021.

Briceno, R. A., Lin, H.-W., and Bolton, D. R. (2012).
Charmed-Baryon Spectroscopy from Lattice QCD with Nf=2+1+1 Flavors.
Phys. Rev., D86:094504.

Chang, C.-H., Qiao, C.-F., Wang, J.-X., and Wu, X.-G. (2006).
Estimate of the hadronic production of the doubly charmed baryon Xi(cc) under GM-VFN scheme.
Phys.Rev., D73:094022.

Chang, C.-H., Wang, J.-X., and Wu, X.-G. (2007).
GENXICC: A Generator for hadronic production of the double heavy baryons Xi(cc), Xi(bc) and Xi(bb).
Comput.Phys.Commun., 177:467–478.

Chen, G., Wu, X.-G., Zhang, J.-W., Han, H.-Y., and Fu, H.-B. (2014).
Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC.

Phys.Rev., D89:074020.

De Rujula, A., Georgi, H., and Glashow, S. L. (1975).
Hadron Masses in a Gauge Theory.
Phys. Rev., D12:147–162.

Ebert, D., Faustov, R. N., Galkin, V. O., and Martynenko, A. P. (2002).
Mass spectra of doubly heavy baryons in the relativistic quark model.
Phys. Rev., D66:014008.

Ebert, D., Faustov, R. N., Galkin, V. O., Martynenko, A. P., and Saleev, V. A. (1997).
Heavy baryons in the relativistic quark model.
Z. Phys., C76:111–115.

Falk, A. F., Luke, M. E., Savage, M. J., and Wise, M. B. (1994).
Heavy quark fragmentation to baryons containing two heavy quarks.
Phys.Rev., D49:555–558.

Fleck, S. and Richard, J. M. (1989).
Baryons with double charm.
Prog. Theor. Phys., 82:760–774.

Flynn, J., Mescia, F., and Tariq, A. S. B. (2003).
Spectroscopy of doubly charmed baryons in lattice QCD.
JHEP, 0307:066.

Gerasyuta, S. M. and Ivanov, D. V. (1999).
Charmed baryons in bootstrap quark model.
Nuovo Cim., A112:261–276.

Gershtein, S., Kiselev, V., Likhoded, A., and Onishchenko, A. a. (1999a).
Spectroscopy of doubly heavy baryons.
Heavy Ion Phys., 9:133–144.

Gershtein, S. S., Kiselev, V. V., Likhoded, A. K., and Onishchenko, A. I. (1999b).
Spectroscopy of doubly charmed baryons: Xi(cc)+ and Xi(cc)++.
Mod. Phys. Lett., A14:135–146.

Gershtein, S. S., Kiselev, V. V., Likhoded, A. K., and Onishchenko, A. I. (2000).
Spectroscopy of doubly heavy baryons.
Phys. Rev., D62:054021.

He, D.-H., Qian, K., Ding, Y.-B., Li, X.-Q., and Shen, P.-N. (2004).
Evaluation of spectra of baryons containing two heavy quarks in bag model.
Phys. Rev., D70:094004.

Itoh, C., Minamikawa, T., Miura, K., and Watanabe, T. (2000).
Doubly charmed baryon masses and quark wave functions in baryons.
Phys. Rev., D61:057502.

Karliner, M. and Rosner, J. L. (2014).
Baryons with two heavy quarks: Masses, production, decays, and detection.

Kerbikov, B. O., Polikarpov, M. I., and Shevchenko, L. V. (1990).
Multi - Quark Masses and Wave Functions Through Modified Green's Function Monte Carlo Method.
Nucl. Phys., B331:19.

Kiselev, A. V., Berezhnoy, A. V., and Likhoded, A. K. (2017).
Quark-diquark structure and masses of doubly charmed baryons.

Kiselev, V. and Likhoded, A. (2002).

Baryons with two heavy quarks.
Phys.Usp., 45:455–506.

Korner, J. G., Kramer, M., and Pirjol, D. (1994).
Heavy baryons.
Prog. Part. Nucl. Phys., 33:787–868.

Lewis, R., Mathur, N., and Woloshyn, R. M. (2001).
Charmed baryons in lattice QCD.
Phys. Rev., D64:094509.

Lichtenberg, D. B., Roncaglia, R., and Predazzi, E. (1996).
Mass sum rules for singly and doubly heavy flavored hadrons.
Phys. Rev., D53:6678–6681.

Liu, L., Lin, H.-W., Orginos, K., and Walker-Loud, A. (2010).
Singly and Doubly Charmed J=1/2 Baryon Spectrum from Lattice QCD.
Phys. Rev., D81:094505.

Mathur, N., Lewis, R., and Woloshyn, R. M. (2002).
Charmed and bottom baryons from lattice NRQCD.
Phys. Rev., D66:014502.

Migura, S., Merten, D., Metsch, B., and Petry, H.-R. (2006).
Charmed baryons in a relativistic quark model.
Eur. Phys. J., A28:41.

Namekawa, Y. (2012).
Charmed baryon spectroscopy on the physical point in 2+1 flavor lattice QCD.
PoS, LATTICE2012:139.

Narodetskii, I. M. and Trusov, M. A. (2002a).
The Doubly heavy baryons in the nonperturbative QCD approach.
In *The structure of baryons. Proceedings, 9th International Conference, Baryons 2002, Newport News, USA, March 3-8, 2002*, pages 639–642.

Narodetskii, I. M. and Trusov, M. A. (2002b).
The Heavy baryons in the nonperturbative string approach.
Phys. Atom. Nucl., 65:917–924.
[Yad. Fiz.65,949(2002)].

Peterson, C., Schlatter, D., Schmitt, I., and Zerwas, P. M. (1983).
Scaling Violations in Inclusive e+ e- Annihilation Spectra.
Phys.Rev., D27:105.

Richard, J.-M. (1994).
Hadrons with two heavy quarks.
In *Workshop on the Future of High Sensitivity Charm Experiments: CHARM2000 Batavia, Illinois, June 7-9, 1994*, pages 95–102.

Richard, J. M. and Stancu, F. (2005).
Double charm hadrons revisited.
Bled Workshops Phys., 6(1):25–31.

Roberts, W. and Pervin, M. (2008).
Heavy baryons in a quark model.
Int. J. Mod. Phys., A23:2817–2860.

Roncaglia, R., Dzierba, A., Lichtenberg, D. B., and Predazzi, E. (1995a).
Predicting the masses of heavy hadrons without an explicit Hamiltonian.
Phys. Rev., D51:1248–1257.

Roncaglia, R., Lichtenberg, D. B., and Predazzi, E. (1995b).
Predicting the masses of baryons containing one or two heavy quarks.
Phys. Rev., D52:1722–1725.

Silvestre-Brac, B. (1996a).

Spectroscopy of baryons containing heavy quarks.
Prog. Part. Nucl. Phys., 36:263–273.

Silvestre-Brac, B. (1996b).
Spectrum and static properties of heavy baryons.
Few Body Syst., 20:1–25.

Tong, S.-P., Ding, Y.-B., Guo, X.-H., Jin, H.-Y., Li, X.-Q., Shen, P.-N., and Zhang, R. (2000).
Spectra of baryons containing two heavy quarks in potential model.
Phys. Rev., D62:054024.

Vijande, J., Garcilazo, H., Valcarce, A., and Fernandez, F. (2004).
Spectroscopy of doubly charmed baryons.
Phys. Rev., D70:054022.

Weng, M. H., Guo, X. H., and Thomas, A. W. (2011).
Bethe-Salpeter equation for doubly heavy baryons in the covariant instantaneous approximation.
Phys. Rev., D83:056006.

Zhang, J.-R. and Huang, M.-Q. (2008).

Doubly heavy baryons in QCD sum rules.
Phys. Rev., D78:094007.

Zhang, J.-W., Wu, X.-G., Zhong, T., Yu, Y., and Fang, Z.-Y. (2011).
Hadronic Production of the Doubly Heavy Baryon Ξ_{bc} at LHC.
Phys.Rev., D83:034026.