Double heavy baryons from the theoretical point of view

ICPPA 2018, Moscow

A. Berezhnoy[1], A. Likhoded[2], A. Luchinsky[2]

[1]SINP MSU, [2]IHEP

26.10.2018

Contents

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:

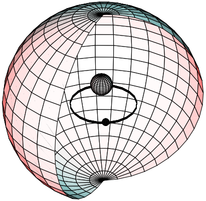
$$m_Q \gg m_{Q_1} \cdot v, m_{Q_2} \cdot v \gg m_{Q_1} v^2, m_{Q_2} v^2 \gg \Lambda_{\rm QCD}$$

(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: diquark in $\bar{3}_c$ + quark-diquark system.
- The total spin of the diquark is a good quantum number within this approach.

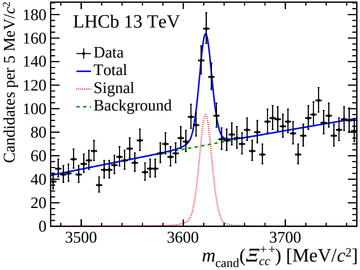
The alternative way: the solving of three-body problem [Albertus et al., 2007a, Albertus et al., 2007b] and much earlier work [Kerbikov et al., 1990].

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, 2002a].

Observation of Ξ_{cc}^{++} at LHCb



$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [Aaij et al., 2017b]

Mass of doubly charmed state [Aaij et al., 2017b]:

$$m_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72(\mathrm{stat}) \pm 0.27(\mathrm{syst} \pm 0.14\,(\Lambda_c^+)\ \mathrm{MeV}/c^2$$

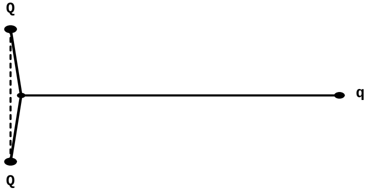
Confirmed in mode $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [Aaij et al., 2018a]

Lifetime is also measured [Aaij et al., 2018b]:

$$\tau_{\Xi_{cc}^{++}} = 0.256\,^{+0.024}_{-0.022}\,(\mathrm{stat})\ \pm 0.014\,(\mathrm{syst})\ \mathrm{ps}$$

Spectroscopy

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



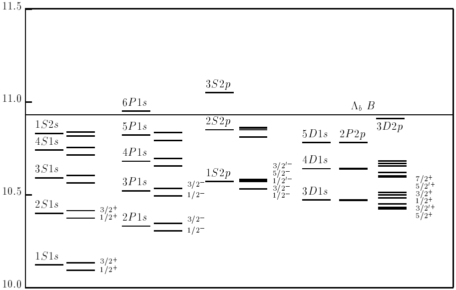
To obtain the spectrum of family of doubly heavy baryons we need:

- 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

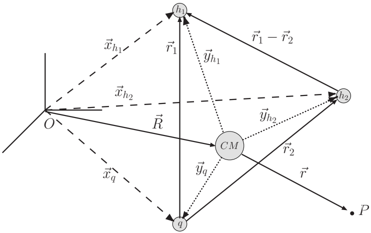
Mass spectrum of Ξ_{cc} baryons in GeV.

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	$\delta_{12} = \delta_{13} = \delta_{23} = 63.47 \pm 8.60$	$\langle r_{12}^2\rangle^{1/2} = \langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.118 \pm 0.034$
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	$\delta_{12} = 50.30 \pm 2.53$ $\delta_{13} = \delta_{23} = 18.63 \pm 1.22$	$\langle r_{12}^2\rangle^{1/2} = 2.238 \pm 0.044$ $\langle r_{13}^2\rangle^{1/2} = \langle r_{23}^2\rangle^{1/2} = 2.842 \pm 0.030$

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:

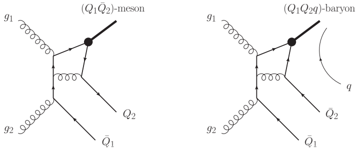
$$(Q_1\bar{Q}_2)_{1_c} \Rightarrow [Q_1 Q_2]_{\bar{3}_c}$$

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

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

$$|R(0)^{Q_1 Q_2}_{\bar{3}_c}|^2 \approx \frac{|R(0)^{Q_1\bar{Q}_2}_{1_c}|^2}{3}$$

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 $[Q_1 Q_2]\bar{3}_c$ 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 $[Q_1 Q_2]_{\bar{3}_c} \to (Q_1 Q_2 q)$?

Q_1Q_2-diquark production amplitude

$$A^{SJj_z} = \int T^{Ss_z}_{Q_1\bar{Q}_1Q_2\bar{Q}_2}(p_i, k(\vec{q})) \cdot \left(\Psi^{Ll_z}_{[Q_1Q_2]_{\bar{3}_c}}(\vec{q})\right)^* \cdot C^{Jj_z}_{s_z l_z} \frac{d^3\vec{q}}{(2\pi)^3},$$

where $T^{Ss_z}_{Q_1\bar{Q}_1Q_2\bar{Q}_2}$ is an amplitude of the hard production of two heavy quark pairs;
$\Psi^{Ll_z}_{[Q_1Q_2]_{\bar{3}_c}}$ is the diquark wave function (color antitriplet);
J and j_z are the total angular momentum and its projection on z-axis in the $[Q_1Q_2]_{\bar{3}_c}$ rest frame;
L and l_z are the orbital angular momentum of bc-diquark and its projection on z-axis;
S and s_z are Q_1Q_2-diquark spin and its projection;
$C^{Jj_z}_{s_z l_z}$ are Clebsh-Gordon coefficients;
p_i are four momenta of diquark, $\bar{Q}_1$ quark and $\bar{Q}_2$ quark;
$\vec{q}$ is three momentum of Q_1-quark in the Q_1Q_2-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 $k(\vec{q})$

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

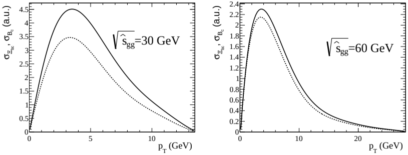
and, particularly, for the S-wave states

$$A \sim R_S(0) \cdot T_{Q_1\bar{Q}_1Q_2\bar{Q}_2}(p_i)|_{\vec{q}=0},$$

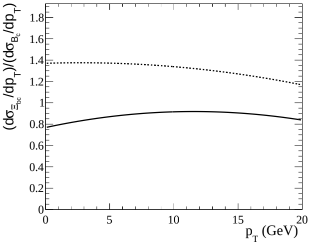
where $R_S(0)$ is a value of radial wave function at origin.

Double heavy baryon production in the hadronic interaction

Ξ_{bc} p_T distribution v.s. B_c p_T distribution $(|R_{B_c}(0)|^2 = |R_{[bc]_{\bar{3}}}(0)|^2)$



Predictions for LHCb $(|R_{B_c}(0)|^2 = |R_{[bc]_{\bar{3}}}(0)|^2)$



model	$\lvert R_{[bc]_{\bar{3}}}(0)\rvert^2/\lvert R_{B_c}(0)\rvert^2$
Buchmüller-Tye potential [Kiselev and Likhoded, 2002a, Gershtein et al., 1997]	0.31
RM I [Ebert et al., 2003, Ebert et al., 2002]	0.26
RM II [Ebert et al., 2011], [Galkin, private communication]	0.32

$$\frac{\sigma_{\Xi_{bc}}}{\sigma_{B_c}} \approx \frac{|R_{[bc]_{\bar{3}}}(0)|^2}{|R_{B_c}(0)|^2} \approx \frac{1}{3}$$

It is wrong for Ξ_{cc} and $J/\psi + c$ productions due large DPS contribution to $J/\psi + c$:

$$\sigma_{\Xi_{cc}} \ll \sigma_{J/\psi+c}$$

[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]

Total width within OPE

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

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

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

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

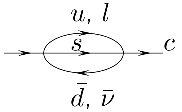
$$C_+ = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{33-2n_f}}, \quad C_- = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{-12}{33-2n_f}}$$

where n_f is the number of flavors.

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

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

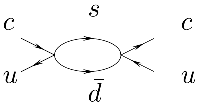
Spectator contribution:



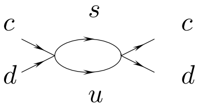
Main features:

- $\bar{c}c$ — 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.

Pauli interference:



Weak scattering:



Ξ_{cc}^{++}, Ξ_{cc}^{+} lifetimes

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

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

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

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

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

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

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

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

Model parameters and life time estimation

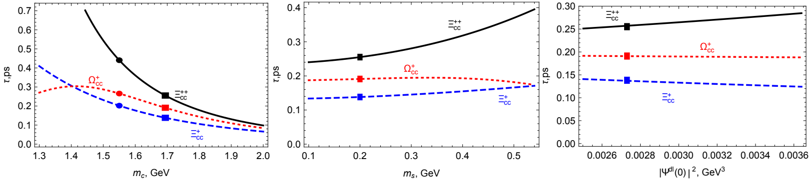
m_c, m_q, $M(\Xi_{cc}^{++})$, $M(\Xi_{cc}^{+})$, T and $\Psi^{dl}(0)$

- $m_c = 1.6$ GeV (taken from 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).
- $|\Psi^{dl}(0)|^2 = (2.7 \pm 0.2) \times 10^{-3}$ GeV^3

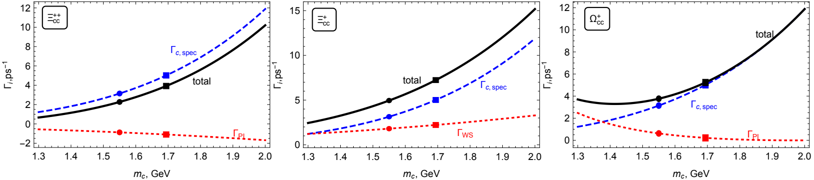
$$\tau(\Xi_{cc}^{++}) = 0.48 \text{ ps} \qquad \tau(\Xi_{cc}^{+}) = 0.12 \text{ ps}$$

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

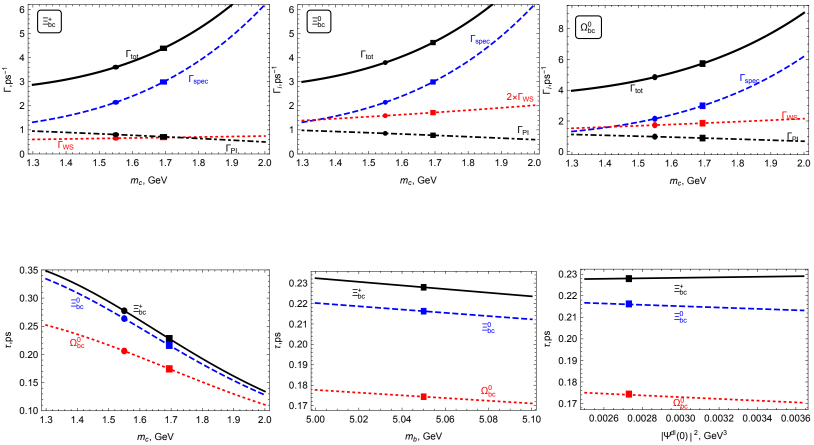
$$m_c = 1.694 \pm 0.03\,\text{GeV}$$



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



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



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.

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		

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

What could be expected at LHCb (Run I + 2015 +2016) for Ξ_{bc} [Blusk, 2017]:

- $N(\Xi_{bc}^{+} \to J/\psi \Xi_{c}^{+}) \sim 12$
- $N(\Xi_{bc}^{+} \to D^0 \Lambda_{c}^{+}) \sim 7$

Definitely, Ξ_{bc} will be observed in Run III.

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.
- 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!

A.Berezhnoy acknowledges from "Basis" Foundation, grant 17-12-244-1.

Backup slides

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, 2002a]	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, 2002a]	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		

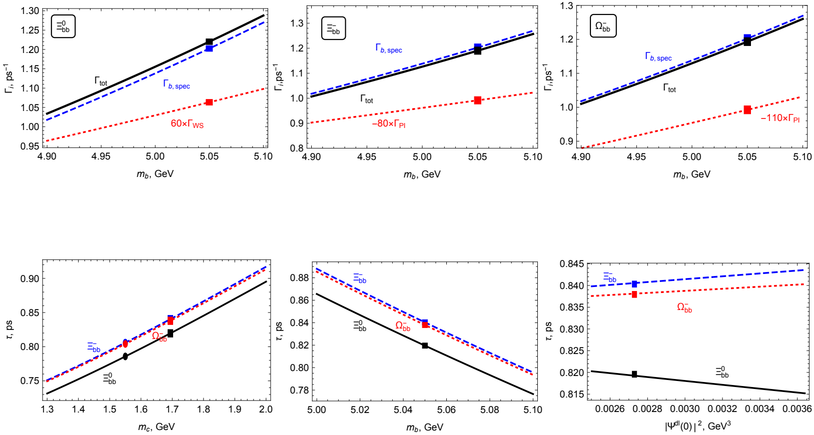
Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (I)

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, 2002a]	3480 ± 50	Potential approach + QCD sum rules
[Narodetskii and Trusov, 2002a]	3690	Nonperturbative string
[Ebert et al., 2002]	3620	Relativistic quark-diquark

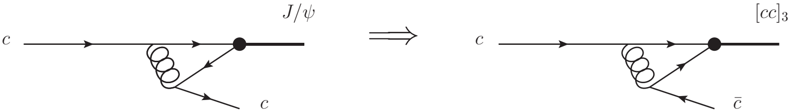
Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (II)

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

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



Fragmentation to diquark



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

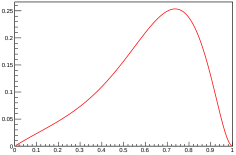
$$Q(\vec{p}) \xrightarrow{D(z)dz} [QQ]_{\bar{3}_c}(z\vec{p})$$

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

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.

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



Comparison with other Results

Karliner, Rosner // PRD 90 (2014) 094007

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

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

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

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

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

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

No lifetime predictions presented
OPE $\Rightarrow \tau_{\Xi_{cc}^{++}} = 0.37\text{ ps}$

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

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

Dimension 7 operators

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

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 $\xi(1) = 1$.

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

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

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

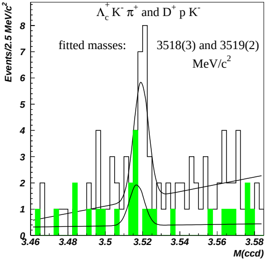
SELEX results

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].

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

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

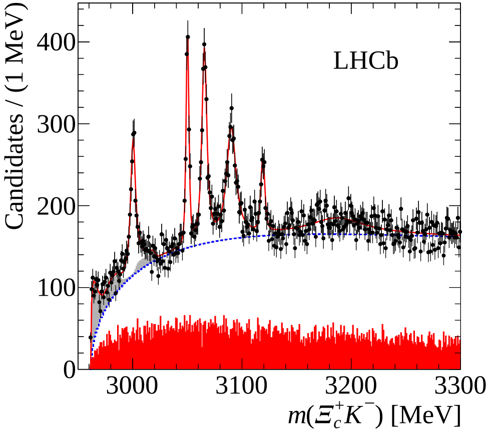
No confirmation from other experiments.



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

For fist time these problems were discussed in [Kiselev and Likhoded, 2002b].

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



[Aaij et al., 2017a]

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}^{++}.

Aaij, R. et al. (2018a).
First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$.
Phys. Rev. Lett., 121(16):162002.

Aaij, R. et al. (2018b).
Measurement of the Lifetime of the Doubly Charmed Baryon Ξ_{cc}^{++}.
Phys. Rev. Lett., 121(5):052002.

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.

Blusk, S. (2017).
Experimental aspects for discovering x_{bc}.
CERN.
Workshop on heavy hadron spectroscopy, CERN,17-18 Jul 2017, `https://indico.cern.ch/event/646144/timetable/`.

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., and Galkin, V. O. (2003).
Properties of heavy quarkonia and B_c mesons in the relativistic quark model.
Phys. Rev., D67:014027.

Ebert, D., Faustov, R. N., and Galkin, V. O. (2011).
Spectroscopy and Regge trajectories of heavy quarkonia and B_c mesons.
Eur. Phys. J., C71:1825.

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., Kiselev, V., Likhoded, A., Tkabladze, A., Berezhnoy, A., et al. (1997).
Theoretical status of the B(c) meson.

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. (2002a).

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

Kiselev, V. and Likhoded, A. (2002b).
Comment on 'First observation of doubly charmed baryon Xi(cc)+'.

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)].

Ocherashvili, A. et al. (2005).

Confirmation of the double charm baryon Xi+(cc)(3520) via its decay to p D+ K-.
Phys.Lett., B628:18–24.

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.