Doubly heavy baryons from the theoretical point of view

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Abstract. The theoretical analysis of production, lifetime, and decays of doubly heavy baryons is presented. The lifetime of \(\Xi^{++}_{cc}\) baryon recently measured by the LHCb Collaboration is used to estimate the lifetimes of other doubly heavy baryons. The production and the possibility of observation of \(\Xi_{bc}\) baryon at LHC are discussed.

1. Introduction

Doubly heavy baryons are extremely interesting objects that allow us to take a fresh look at the problems of the production and hadronization of heavy quarks. These baryons consist of two heavy and one light quarks and therefore, unlike ordinary heavy baryons, are characterized by several scales at once:

\[ m_{Q_1,2} \gg m_{Q_1} \cdot v, m_{Q_2} \cdot v \gg \Lambda_{QCD}, \tag{1} \]

where \(m_{Q_1,2}\) are masses of heavy quarks, and \(v\) is there velocity inside the quarkonium [1].

It is worth to mention, that a baryon with one heavy quark is characterized by only two scales, namely, the mass of the heavy quark and \(\Lambda_{QCD}\). In the limit \(m_{Q_1,2} \to \infty\) a heavy diquark interacts with a light quark as heavy anti-quark and, therefore, it is quite natural to subdivide calculating the characteristics of doubly heavy quarkonium in two stages: the calculation of the properties of the heavy diquark and the subsequent calculation of the properties of the system of quark-diquark.

The problems of production and decays of such systems was of interest to researchers for many years. But the last year was special because it was marked by the discovery of the doubly charmed \(\Xi^{++}_{cc}\) baryon in the decay mode \(\Lambda^{+} c K^{-} \pi^{+} \pi^{+}\) [2]. The LHCb Collaboration observed hundreds of such particles. This discovery was confirmed by the observation of decay \(\Xi^{++}_{cc} \to \Xi^{+} \pi^{+}\) [3]. Both these studies greatly revived the research activities in this direction. In this study we discuss the perspectives of further research of doubly heavy baryon states: their decays, productions and possibility of observation of excited states (see details in [4]).

2. Doubly heavy baryon production

It is natural to use a two-step procedure to produce a doubly heavy baryon. In the first calculation step, a doubly heavy diquark is produced perturbatively in the hard interaction. In the second step, a doubly heavy diquark is transformed to the baryon within the soft hadronization process.

Our calculations of doubly heavy diquark production were done within the following approach:
(i) the color singlet model for doubly heavy mesons and the color triplet model for doubly heavy baryons;
(ii) the contribution from scattering of sea heavy quark and gluon ($Q_1 g \rightarrow Q_1 + Q_2 + \bar{Q}_2$) does not take into account to avoid double counting;
(iii) the contribution of color sextet state to baryon production is neglected;
(iv) the doubly heavy diquark is hadronized by joining with a light quarks $u, d$ and $s$ in proportion $1 : 1 : 0$ with probability equal to 1.

The dominant contribution to the production cross under LHCb kinematics conditions comes from gluonic interaction, as well as for the $B_c$ meson:

$$gg \rightarrow \Xi_{bc} + \bar{b}c.$$ 

Our estimations for that process show that difference of yields of $\Xi_{bc}$ and $B_c$ is mostly determined by the difference of wave functions:

$$\frac{\sigma_{\Xi_{bc}}}{\sigma_{B_c}} \sim \frac{|R_{[bc]}(0)|^2}{|R_{B_c}(0)|^2}. \tag{2}$$

We estimate the ratio of yields $\Xi_{bc}$ and $B_c$ for hadronic interactions at $\sqrt{s} = 13$ TeV for several scales ($\mu_R = \mu_F = 10$ GeV, $\mu_R = \mu_F = E_{T,\Xi_{bc}}$, $\mu_R = \mu_F = 2E_{T,\Xi_{bc}}$) and find, that the dependence of this value on scale choice is unessential (the CT14LL parameterization [5] is used for PDFs). The main uncertainties come from wave functions and from choice of mass values for $b$ and $c$ quarks. In figure 1 we show the ratio of yields $\Xi_{bc}$ and $B_c$ in hadronic interactions as a function of $p_T$ at $\sqrt{s} = 13$ TeV, for the similar masses ($m_b = 4.8$ GeV, $m_c = 1.5$ GeV) and for different masses ($m_b = 4.8$ GeV and $m_c = 1.5$ GeV for $B_c$ production, and $m_b = 4.9$ GeV and $m_c = 1.7$ GeV for $\Xi_{bc}$ production). Here we also put $|R_{B_c}(0)|^2 = |R_{[bc]}(0)|^2$. One can see, that these distributions are approximately flat. Thus, one can conclude, that the estimation (2) is approximately valid for all transverse momenta.

For all available models [1, 6, 7, 8, 9, 10] we obtain that

$$\frac{\sigma_{\Xi_{bc}}}{\sigma_{B_c}} \lesssim \frac{1}{3}. \tag{3}$$

It is worth to note that both the numerator and the denominator in (3) will be modified by the feed-down from excitations. However we believe, that in ratio these contributions will approximately canceled out. The obtained ratio value $\sigma_{\Xi_{bc}}/\sigma_{B_c}$ coincides with that used in talk [11].

Considering absolute cross section value $\Xi_{bc}$ of baryon production at LHCb ($\sqrt{s} = 13$ TeV, $2.0 < y_{\Xi_{bc}} < 4.5$), we estimate it as $10 \div 25$ nb depending on scale values. The feed-down from excitations can be estimated as 20-30 %.

It is worth to mention, that an analogous ratio can not be valid for $J/\psi + c$ and $\Xi_{cc}$ due to the large contribution of DPS to the associative $J/\psi$ and $c$ production.

3. Doubly heavy baryon decays within OPE method

In accordance with Operator Product Expansion (OPE) and optic theorem the life time of doubly heavy baryon $B$ can be represented as

$$\Gamma_B = \frac{1}{2m_B} \langle B | T | B \rangle, \tag{4}$$
where operator $\mathcal{T}$ is

$$\mathcal{T} = \text{Im} \int d^4x \left\{ \hat{T} H_{\text{eff}}(x) H_{\text{eff}}(0) \right\}, \quad (5)$$

with

$$H_{\text{eff}} = \frac{G_F}{2 \sqrt{2}} V_{q_1q_4} V_{q_2q_3}^* [C_+(\mu) O_+ + C_-^{(\mu)} O_-], \quad (6)$$

In the above expression Wilson coefficients $C_\pm^{(\mu)}$ are equal to

$$C_+^{(\mu)} = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{-\frac{6}{3 - 2n_f}}, \quad C_-^{(\mu)} = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^\frac{12}{3 - 2n_f}, \quad (7)$$

where $\alpha_s(\mu)$ is a running strong coupling constant calculated within two-loop approximation and $n_f$ is a number of active flavors. The operators $O_\pm$ in (6) are determined as follows:

$$O_\pm = \left[ \bar{q}_1 \alpha \gamma (1 - \gamma_5) q_2 \right] \left[ \bar{q}_3 \gamma \gamma (1 - \gamma_5) q_4 \right] (\delta_{\alpha\beta} \delta_{\gamma\delta} \pm \delta_{\alpha\delta} \delta_{\beta\gamma}), \quad (8)$$

where $\alpha, \beta, \gamma, \delta$ are color indices of quarks.

For large energy of heavy quark decay one can represent $\mathcal{T}$ (5) a set of local operators ordered by increasing of their dimension. The contribution of high dimension term are suppressed by inverse powers of heavy quark mass $m_Q$, and therefore only several first terms contribute to the decay value. This method was broadly used for the calculation of lifetimes of heavy hadrons [12, 13, 14, 15, 16, 17, 18, 19], as well as doubly heavy hadrons [20, 21]. It was shown in the cited papers the operators of dimension 3 and 5:

$$O_{QQ} = (\bar{Q} Q), \quad O_{QG} = (\bar{Q} \sigma_{\mu\nu} G^{\mu\nu} Q), \quad (9)$$

correspond to the spectator decay of heavy quark and give the main contribution to the value (4). The following operator of dimension 6 can also give noticable contribution to the decay process:

$$O_{2Q2q} = (\bar{Q} \Gamma q)(\bar{q} \gamma Q). \quad (10)$$

The other operators of dimension: $O_{61Q} = \bar{Q} \sigma_{\mu\nu} \gamma \lambda D^{\mu} G^{\nu\lambda} Q$, $O_{62Q} = \bar{Q} D_{\mu} G^{\mu\nu} \Gamma_{\nu} Q$, contribute insignificantly comparing with (10).

Typical Feynman diagrams for the discussed processes are shown in figure 2. In accordance with OPE method the following mechanisms can contribute to the total decay width:

- Spectator mechanism (the operator (9) and the figure 2(a), see also [20, 22, 23, 24, 25, 26, 27]),
- Weak scattering, WS (the operator (10) and the figure 2(b) [20, 28, 29, 30, 31]),
- Pauli-interference, PI (the operator (10) and the figures 2(c), (d) [21]).

It is clear from the results presented above that in OPE formalism theoretical predictions of doubly heavy baryons’ lifetimes depend on such input parameters as quark masses, wave function at the origin, etc. In paper [31] the following values of these parameters were used:

$$V_{cs} = 0.9745, \quad V_{cb} = 0.04, \quad (11)$$

$$T = 0.4 \text{ GeV}, \quad |\Psi^{d_1}(0)|^2 = (2.7 \pm 0.2) \times 10^{-3} \text{ GeV}^3, \quad (12)$$
We will discuss the results of these papers in the next subsection, while here we consider quark constituent masses obtained from analysis of similar quark masses. Our analysis shows that experimental masses as free and check the dependence of doubly heavy baryons lifetimes on the variation of these parameters. It can be seen from these figures that $\tau_{\Xi_{cc}^{++}}$ is most sensitive to change of $c$-quark mass. Our analysis shows that experimental value (15) can be reconstructed with the following parameter values:

$$m_c = 1.73 \pm 0.07 \text{ GeV}, \quad m_s = 0.35 \pm 0.20 \text{ GeV}.$$  

This choice however leads to the following values of $\Xi_{cc}^{++}$ baryon mass and lifetime:

$$M_{\Xi_{cc}^{++}} = 3.478 \text{ GeV}, \quad \tau_{\Xi_{cc}^{++}} = 0.44 \text{ ps}.  \quad (14)$$

These results, unfortunately, disagree with recent experimental data [2, 32]:

$$M_{\Xi_{cc}^{++}}^{\exp} = (3621.40 \pm 0.72 \pm 0.27 \pm 0.14) \text{ MeV}, \quad \tau_{\Xi_{cc}^{++}}^{\exp} = 0.256^{+0.024}_{-0.022} \pm 0.014 \text{ ps},  \quad (15)$$

so some change of parameters is required. It should be noted that the values (13) correspond to constituent quark masses obtained from analysis of $D$-mesons’ lifetimes. In papers [33, 34] it was proposed that a slightly different masses should be used in the case of doubly heavy baryons. We will discuss the results of these papers in the next subsection, while here we consider quark masses as free and check the dependence of doubly heavy baryons lifetimes on the variation of these parameters.

In figure 3 we show model parameter dependence of $\Xi_{cc}^{++}$ lifetime, while figure 4 shows $m_c$ dependence of different channels that contribute to this lifetime. It can be seen from these figures that $\tau(\Xi_{cc}^{++})$ is most sensitive to change of $c$-quark mass. Our analysis shows that experimental value (15) can be reconstructed with the following parameter values:

$$m_c = 1.73 \pm 0.07 \text{ GeV}, \quad m_s = 0.35 \pm 0.20 \text{ GeV}.  \quad (16)$$
As for dimension 6 operators, in complete agreement with OPE selection rules contrast to.. In the following we will use constituent value
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With these masses we have \( \tau(\Xi_{\text{cc}}^{*+}) = 0.26 \pm 0.03 \) ps. It is to note, that the spectator decay channel gives the main contribution and increases with the increase of charm quark mass. In addition, PI channel gives destructive contribution in this case, which leads to increase of the lifetime. As for weak scattering mechanism, it is forbidden for \( \Xi_{\text{cc}}^{*+} \) decay.

Using the approach described above, it is easy to calculate also lifetimes of \( \Xi_{\text{cc}}^{*+} \) and \( \Omega_{\text{cc}}^{*+} \) baryons:

\[
\tau(\Xi_{\text{cc}}^{*+}) = 0.14 \pm 0.01 \text{ ps}, \quad \tau(\Omega_{\text{cc}}^{*+}) = 0.18 \pm 0.02 \text{ ps}. \tag{17}
\]

Lifetime and decay width dependencies on parameters are shown in figures 3, 4. In the case of \( \Xi_{\text{cc}}^{*+} \) baryon the PI channel is forbidden, thus only the spectator decay and the weak scattering give contributions. For for \( \Omega_{\text{cc}}^{*+} \) baryon the spectator and PI channels are important. The contribution of the last one is positive. As a result theoretical predictions for the lifetimes of \( \Xi_{\text{cc}}^{*+} \) and \( \Omega_{\text{cc}}^{*+} \) are smaller than for \( \Xi_{\text{cc}}^{*+} \) particle.

Let us now consider lifetimes of \( bc \)-baryons \( \Xi_{bc}^0, \Xi_{bc}^+, \) and \( \Omega_{bc}^0 \). The lifetime dependences on parameters are shown in figure 5. In the following we will use constituent value \( m_b = 5.05 \text{ GeV} \) for \( b \)-quark mass and (16) for \( m_{c,s} \). In figure 6 we show \( m_c \) dependence of different channel contributions for these baryons. From presented results it is clear, that \( c \)-quark spectator decay is dominant for the considered baryons, while contributions of \( b \)-quark spectator decay is suppressed by \( V_{cb} \) matrix element. As for dimension 6 operators PI and WS, their contributions are suppressed by large \( b \)-quark mass and are small. It is interesting to note, however, that, in contrast to \( cc \) baryons, in the case of \( bc \)-baryons both PI and WS channels are not forbidden for all considered particles.

In the case of \( bb \)-baryons \( \Xi_{bb}^0, \Xi_{bb}^+, \) and \( \Omega_{bb}^- \) spectator \( b \)-quark decay gives the dominant contribution. As for dimension 6 operators, in complete agreement with OPE selection rules

\[
\begin{align*}
&\text{Figure 4. The partial widths for different operators for doubly charmed baryons (in ps}\^{-1}\text{): operators of dimension 3 and 5 corresponds to the spectator mechanism (dashed blue curve), operators of dimension 6 corresponding to the weak scattering and Pauli interference (red dotted curve), the total width (black solid curve). The dots correspond to the predictions of [31].} \\
&\text{Figure 5. Lifetimes in ps for } \Xi_{bc}^+ \text{ (solid black curve), } \Xi_{bc}^0 \text{ (blue dashed curve) and } \Omega_{bc}^0 \text{ (red dotted curve) as a function of the model parameters. The results of [31] are shown by dots.}
\end{align*}
\]
Figure 6. The partial widths for different operators for \( bc \) baryons (in ps\(^{-1} \)): operators of dimension 3 and 5 corresponds to the spectator mechanism (dashed blue curve), operators of dimension 6 corresponding to the weak scattering and Pauli interference (red dotted and black dash-dotted curves respectively), the total width (black solid curve). The dots correspond to the predictions of [31].

Figure 7. Decay widths for \( bb \) baryons. Designations are as in figure 4.

Figure 8. Lifetimes in ps for \( \Xi_{bc}^0 \) (solid black curve), \( \Xi_{bc}^- \) (blue dashed curve) and \( \Omega_{bc}^- \) (red dotted curve) as a function of the model parameters. The results of [31] are shown by dots.

Their contributions are suppressed by large quark mass. As a result, lifetime values are close to each other. Parameter dependence of the lifetimes and decay widths of these baryons are shown in figures 7 and 8.

4. Observation Perspectives
Here we briefly discuss the observation possibilities of doubly heavy baryons at LHC. As it was already mentioned the observation of \( \Xi_{cc}^{++} \) baryon has been done by the LHCb Collaboration in the decay mode \( \Lambda_c^+K^−\pi^+\pi^+ \) [2] and confirmed in the decay mode \( \Xi_{cc}^{+}\pi^+\pi^+ \) [3].

The next step is the observation of \( \Xi_{cb} \) baryon. In spite of large number of theoretical predictions for branching fractions (see, for example, [1, 35, 36, 37, 38, 39, 40] and table 1), the "golden mode" is not found yet. Of course, the greater branching fraction value, the more chances for the decay mode to be observed. But the decay branchings of intermediate particles
are also very important. In addition, as it is shown in [11], the possibility of the experiment also must be taken into account. For example, each extra track in final state decreases the registration efficiency. That is why understanding the experiment features is very important for searching the most promising decay modes. We share cautious optimism of [11] about the observation of lifetimes of doubly heavy baryons. However, in the case of \( \Xi_{cc} \) parameter with pretty good accuracy and to make the lifetime predictions for other doubly heavy baryons.

Table 1. Branching fractions of the exclusive decays.

| Mode          | [39, 1] | [40] | Mode          | [39, 1] | [40] | Mode          | [39, 1] | [40] |
|---------------|---------|------|---------------|---------|------|---------------|---------|------|
| \( \Xi_{cc}^{++} \to \Xi_{cc}^{+} \rho^+ \) | 46.8    | 14.2 | \( \Xi_{cc}^{+} \to \Xi_{cc}^0 \rho^+ \) | 33.6    | 4.66 | \( \Omega_{cc}^+ \to \Omega_{cc}^0 \rho^+ \) | –       | 24.2 |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 16.8    | 5.39 | \( \Xi_{cc}^{+} \to \Xi_{cc}^0 \pi \) | 11.2    | 2.4  | \( \Omega_{cc}^+ \to \Omega_{cc}^0 \pi \) | –       | 7.05 |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \rho^+ \) | 21.7    | 6.24 | \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \rho^+ \) | 20.1    | 2.36 | \( \Omega_{bc}^0 \to \Omega_{bc}^0 \rho^+ \) | –       | 18.  |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 7.7     | 3.25 | \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \pi \) | 7.1     | 1.23 | \( \Omega_{bc}^0 \to \Omega_{bc}^0 \pi \) | –       | 4.57 |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 4.4     | 2.3  | \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \ell \nu_{\ell} \) | 4.1     | 0.867| \( \Omega_{bc}^0 \to \Omega_{bc}^0 \ell \nu_{\ell} \) | –       | 6.   |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 14.9    | 2.59 | \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \ell \nu_{\ell} \) | 14.9    | 1.68 | \( \Omega_{bc}^0 \to \Omega_{bc}^0 \ell \nu_{\ell} \) | –       | 4.83 |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 5.7     | 0.617| \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \ell \nu_{\ell} \) | 5.7     | 0.265| \( \Omega_{bc}^0 \to \Omega_{bc}^0 \ell \nu_{\ell} \) | –       | 1.25 |
| \( \Xi_{bc}^{++} \to \Xi_{bc}^{+} \ell \nu_{\ell} \) | 2.2     | 0.213| \( \Xi_{bc}^{+} \to \Xi_{bc}^0 \ell \nu_{\ell} \) | 2.2     | 0.0854| \( \Omega_{bc}^0 \to \Omega_{bc}^0 \ell \nu_{\ell} \) | –       | 0.43 |

5. Conclusions

This article is devoted to theoretical study of total widths, production rates, and observation probabilities of the doubly heavy baryons.

We briefly discussed the production and the possibility of observation of \( \Xi_{bc} \) baryon at LHC, and showed that the kinematical features of \( \Xi_{bc} \) baryon production and \( B_c \) meson production are very similar.

The main efforts were made to estimate the lifetimes of doubly heavy baryons in the framework of Operator Product Expansion (OPE). We studied the lifetime dependence on main parameters of this formalism, which are masses of \( s, c \), and \( b \) quarks and the value of the diquark wave function at the origin. We show, that the spectator heavy quark decays give the main contribution to the lifetimes of doubly heavy baryons. However, in the case of \( \Xi_{cc} \) and \( \Omega_{cc} \) baryons the contributions of the higher dimension terms, such as weak scattering and Pauli interference channels, are also important. For \( bcq \) and \( bbq \) baryons the higher dimension terms are suppressed by the large mass of the heavy quark and do not contribute essentially to the lifetime value.

The lifetime predictions for doubly heavy baryons are most sensitive to the charm quark mass. The knowledge of the experimental value of \( \Xi_{cc}^{++} \) baryon lifetime allowed us to determine this parameter with pretty good accuracy and to make the lifetime predictions for other doubly heavy baryons.

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