Hadronic production of double charmed baryons with excited diquark

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Abstract. We discuss the prospects of the observation of double heavy baryons Ξcc, Ωcc with excited diquark (S and P excitations) in experiments at LHC. P-wave excitations of a diquark in double charmed baryons are supposed to be quite narrow since their decay into the ground state is highly suppressed. Relative yields of S-wave and P-wave excitations have been estimated within pQCD for the LHCb kinematics.

1. Introduction
The problems of production and decays of the doubly heavy baryons was of interest to researchers for many years (see for example [1]). Such systems consist of two charm quarks and one light quark, and, therefore, it is quite natural to subdivide calculating the characteristics of doubly heavy baryon 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 [1]. This essentially simplifies a theoretical research of doubly heavy baryons, and allows to obtain the detailed prediction of their properties.

For many years, these particles could not be observed experimentally. But finally the fist doubly heavy baryon Ξcc+ has been observed by the LHCb Collaboration in the decay mode Λcc+ K−π+π+[5]. The observation has been already confirmed in the mode Ξc+π+ [6]. The lifetime of this new state also has been measured [7]. This circumstance greatly revived the research activities in this direction. In this article we discuss the possibilities of further research of doubly charm baryon states, namely we estimate the yield of the doubly charmed baryons with excited heavy diquark (so-called ρ-exitations, see figure 1).

2. Production
To produce a baryon, it is natural to use a two-step procedure. In the first step of the calculations a double heavy diquark in the anti-triplet color state can be produced perturbatively in the hard interaction. In the second step a double heavy diquark should be transformed to the baryon within the soft hadronization process (see [8, 9, 10, 11, 12, 13] for details).

1 However, it is necessary to note that there are attempts to solve directly the quantum three bodies problem [2, 3, 4]
Figure 1. Schematic representation of $\rho$ and $\lambda$ excited states of $\Xi_{cc}$ baryon. $\rho$ states are states with the excited doubly heavy diquark, $\lambda$ are states with the excited light quark.

The production amplitude can be written as follows:

$$A^{SJz} = \int T^{Ss}_{cc\bar{c}c}(p_i, k(\bar{q})) \cdot \left( \Psi^{Ll}_{\bar{c}c}(\bar{q}) \right)^* \cdot C^{Jz}_{s_1s_2} \frac{d^3\bar{q}}{(2\pi)^3},$$  \hspace{1cm} (1)$$

where $T^{Ss}_{cc\bar{c}c}$ is an amplitude of the hard production of two heavy quark pairs; $\Psi^{Ll}_{\bar{c}c}$ is the diquark wave function (color antitriplet); $J$ and $J_z$ are the total angular momentum and its projection on $z$-axis in the $[cc\bar{c}c]$ rest frame; $L$ and $l_z$ are the orbital angular momentum of $cc$-diquark and its projection on $z$-axis; $S$ and $s_z$ are $cc$-diquark spin and its projection; $C^{Jz}_{s_1s_2}$ are Clebsh-Gordon coefficients; $p_i$ are four momenta of diquark, and $\bar{c}$ quarks; $\bar{q}$ is three momentum of $c$-quark in the $cc$-diquark rest frame (in this frame $(0, \vec{q}) = k(\bar{q})$).

Under assumption of small dependence of $T^{Ss}_{cc\bar{c}c}$ on $k(\bar{q})$ amplitude can be expanded into a series of $\bar{q}$ powers:

$$A \sim \int d^3\bar{q} \Psi^*(\bar{q}) \left\{ T(p_i, \bar{q})|_{\bar{q}=0} + \bar{q} \frac{\partial}{\partial \bar{q}} T(p_i, \bar{q})|_{\bar{q}=0} + \ldots \right\},$$  \hspace{1cm} (2)$$

where the first term provides us the $S$-wave matrix element, the second term – $P$-wave.

Since the spectroscopy of a diquark with two identical quarks puts a restriction on the spin $S$ of a diquark, the formulae are simplified. For $S$-wave states we have $S = 1$ and amplitude is a triplet by $j_z = s_z$:

$$A^{s_z} = \frac{1}{\sqrt{4\pi}} R_S(0) \cdot T^{s_z}_{cc\bar{c}c}(p_i)|_{\bar{q}=0},$$  \hspace{1cm} (3)$$

For $P$-wave states we have $S = 0$ and amplitude is a triplet by $j_z = l_z$:

$$A^{l_z} = i \sqrt{\frac{3}{4\pi}} R'_P(0) \cdot \{ \mathcal{L}^{l_z} T^{l_z}_{cc\bar{c}c}(p_i, \bar{q}) \}|_{\bar{q}=0},$$  \hspace{1cm} (4)$$

where $R_S(0)$ and $R'_P(0)$ are values of radial wave function at origin; $\mathcal{L}^{l_z}$ is a differential operator expressed through the polarization vector $\varepsilon(l_z)_a$:

$$\mathcal{L}^{l_z} = \left( \varepsilon(l_z)_a \frac{\partial}{\partial q^a} \right)^*.$$  \hspace{1cm} (5)
Obviously, a color antitriplet of $cc$-system should be somehow transformed to the $ccq$-baryon. The transverse momentum of light quark $q$ with mass $m_q$ is about $m_q \langle p_T^{ccq} \rangle$, where $p_T^{ccq}$ is a transverse momentum of $ccq$-baryon. For LHCb kinematical conditions such a quark always exists in the quark sea. This is why we assume, that a doubly heavy baryon is hadronized by joining with one of the light quarks $u, d$ and $s$ in proportion $1 : 1 : 0$. We also assume that it is hadronized with unite probability. The latter assumption is pretty much a guess, because diquark has a color charge and therefore strongly interacts with its environment, that could lead to the diquark dissociation.

Alternatively, we could suppose, that the diquark is hadronized within the fragmentation model by analogy with a heavy meson. In the framework of this model the energy loss of the diquark is described by the fragmentation function, which is independent on the processes. The shape of the fragmentation function for a heavy meson can be extracted from the experimental data on $e^+ e^-$ annihilation. Contrary to this the fragmentation function for doubly heavy diquark is not known. However it is reasonably to suppose that this function is quite sharp even for the lightest doubly heavy $cc$-diquark due to the large diquark mass.

Table 1. Wave function values and masses for $cc$-diquark states [14].

| state | wave function | diquark mass |
|-------|---------------|--------------|
| $1S$  | $|R(0)|$, GeV$^{3/2}$ | $m$, GeV |
| $2S$  | 0.566         | 3.20         |
| $3S$  | 0.540         | 3.50         |
| $1P$  | $|R'(0)|$, GeV$^{3/2}$ | $m$, GeV |
| $2P$  | 0.149         | 3.40         |

Table 2. Cross sections and relative yields for $cc$-diquark states.

| state | relative yield | cross section |
|-------|---------------|--------------|
| $r^*$ | $r$, %        | $\sigma$, nb |
| $1S$  | 49 $\div$ 52 | 120 $\div$ 170 |
| $2S$  | 26 $\div$ 27 | 60 $\div$ 90 |
| $3S$  | 18 $\div$ 20 | 40 $\div$ 70 |
| $1P$  | 2             | 4 $\div$ 6 |
| $2P$  | 1 $\div$ 2   | 4 $\div$ 5 |

The calculation technique largely follows one in the works [15, 11]. A full set of 36 leading order gluon-gluon diagrams is engaged for hard production of two $c\bar{c}$-pairs. The $cc$-bound state is described by a color structure $\epsilon_{ijk}/\sqrt{2}$.

For our estimations we take radial wave function values and masses from [14] (see table 1). To obtain the proton-proton cross sections we use PDFs and $\alpha_s$ from CT14 PDF set [16]. The calculations are performed for LHCb detector’s kinematics $2 < \eta < 4.5$, $p_T < 10$ GeV at center-of-mass energy $\sqrt{s} = 13$ TeV. The scale variation from $E_T/2$ to $2E_T$ contributes to uncertainty for cross sections. Final results are given in Table 2 where by relative yield we mean the ratio of cross sections. The relative yield of baryons with doubly charmed diquark in $2S$ and $3S$ states is about 50%. P-wave states of the diquark give only $3 \div 5\%$ of the total yield.

The $p_T$ distributions at $\sqrt{s} = 8$ TeV are very similar to the corresponding distributions at $\sqrt{s} = 13$ TeV and therefore are not presented here. It can be seen in Figs. 3 and 4, that uncertainties for the relative values arising from the scale choice are practically cancel out. Our estimations show that the relative contribution of the excited states slightly increases with transverse momenta. However it doesn’t mean, that excitations should be sought at large transverse momenta, because an absolute yield is greater at small transverse momenta.

3. Transitions to the ground state

The excited states of doubly charmed baryons, lying below the $\Lambda_c D$ threshold, fall into the ground state. The quark-diquark model of a doubly heavy baryon allows one to examine separately the excitations of a light quark and a heavy diquark. Therefore, transitions between the different states of doubly heavy baryon can be categorized into transitions caused by a
change of the light quark state in the baryon and transitions caused by a change of the diquark state. It is anticipated that, if kinematically possible, the hadronic mode dominates, since the predictions for the widths of electromagnetic transitions are much less than for hadronic ones. So the widths of single-photon transitions from \( \lambda \)-excitations to the ground state do not exceed 0.5 MeV in accord with works [17, 18, 19].

According to most predictions for the mass spectra of \( \Xi_{cc} \) and \( \Omega_{cc} \)-baryons families, below the threshold should be two levels corresponding to excitations of the light quark: a spin doublet \( 1S1p \) \((1/2)\) and a spin triplet \( 1S1p \) \((3/2)\). Besides the states attributed to excitations of the light quark, doubly charmed baryon has about five levels relevant to the radial and orbital excitations of the \( cc \)-diquark below the charmed baryon and the charmed meson decay threshold [14, 20]. Furthermore the first orbital and the first radial excitations of the diquark (levels \( 1P1s \) and \( 2S1s \) respectively) lie below the excitations of the light quark.

All research groups suggest that excitations of light degrees of freedom of doubly charmed baryons should be rather broad [21, 22]. There are estimates for the decay width from the

\[ \sigma \]

\[ \text{GeV} \]

\[ \text{nb/GeV} \]

\[ \text{S-wave} \]

\[ \text{P-wave} \]

\[ \text{Figure 2.} \] \( d\sigma/dp_T \) dependence on \( p_T \) for different scales.

\[ \text{Figure 3.} \] \( r^* \) dependence on \( p_T \) for sum of radial excitations for different scales.

\[ \text{Figure 4.} \] \( r \) dependence on \( p_T \) for sum of orbital excitations for different scales.
first radial excitation of the diquark to the ground state $\Xi_{cc}' \rightarrow \Xi_{cc}\pi$ which are comparable in magnitude to the values in case of transitions from $\lambda$-excitations [23]:

$$\Gamma (\Xi_{cc}') = \tilde{g}^2 \ 52 \text{ MeV},$$
$$\Gamma (\Xi_{cc}) = \tilde{g}^2 \ 391 \text{ MeV},$$

where $\tilde{g}$ is of order unity and the decay goes into either levels of doublet $1S1_s$. For the doublet $2S1s$ the designation $\Xi_{cc} (J^P = 1/2^+)$ and $\Xi_{cc}^* (J^P = 3/2^+)$ is used. We note that transitions via both a neutral and a charged pion occur. In $\Omega_{cc}$ spectrum analogous single-pion transitions break the isospin symmetry, and as a result are highly suppressed. The $\Omega_{cc}$ excitations decay into the $\Xi_{cc}$ ground state via kaon emission.

It should be expected that transitions with a change of quantum numbers of the diquark will be rather narrow relative to the transitions between the excitations of the light quark. Let us focus on the transitions from the $P$-wave diquark to the ground state $\Xi_{cc} (J^P = 1/2^-)$ and $\Xi_{cc}^* (J^P = 3/2^-)$, the ground state $\Xi_{cc} (J^P = 1/2^+)$ together with the hyperfine splitting partner $\Xi_{cc}^* (J^P = 3/2^+)$. Such transitions are suppressed as $\Lambda_{QCD}^2/m_c^2$ since they are accompanied by a simultaneous change of the spin and orbital angular momentum of the diquark. Only transitions between states with the same $J$ are allowed: $3/2^- \rightarrow 3/2^+$, $1/2^- \rightarrow 1/2^+$. In [24] the decay widths of $\Xi_{cc}^P$ and $\Xi_{cc}^{P*}$ have been estimated:

$$\Gamma (\Xi_{cc}^P \rightarrow \Xi_{cc}^* \pi) = \lambda_{3/2}^2 112 \text{ MeV},$$
$$\Gamma (\Xi_{cc}^P \rightarrow \Xi_{cc} \pi) = \lambda_{1/2}^2 111 \text{ MeV},$$

where $\lambda_{3/2}, \lambda_{1/2} \sim \Lambda_{QCD}^2/m_c$ and both neutral and charged modes are included. Thus for small values of $\lambda_{1/2}$ and $\lambda_{3/2}$ these states will indeed be metastable, as supposed in [25]. However the difference in numerical predictions for these widths is quite large. In [23] the upper limit for them stands at 28 MeV. Study [26] predicts that the mentioned states $\Xi_{cc}^P$ and $\Xi_{cc}^{P*}$ will be more narrow: 0.3 and 0.6 MeV, correspondingly.

Since the mass difference between the baryon’s ground state and its lowest excitation $\Xi_{cc}^*$ is less than the pion mass, the $1S1s$-multiplet transition can occur via a photon emission only. In $\Xi_{cc}^P \rightarrow \Xi_{cc}^* \pi \rightarrow \Xi_{cc}^* \pi \gamma$ decay a soft photon cannot be detected. Hence in contrast to decay $\Xi_{cc}^P \rightarrow \Xi_{cc}^* \pi$, the peak corresponding to $\Xi_{cc}^{P*}$ will be shifted to $\Delta M^*$, which is about 100 MeV according [14] and about 130 MeV according [27], and will have an extra widening, which can be estimated as:

$$\Delta M_{\text{inv}} \approx 2\Delta M^* \left( \frac{\Delta M}{M} \right)^2 - \left( \frac{m_\pi}{M} \right)^2 \approx 10 \text{ MeV},$$

here $M$ - mass of the ground state, $M (\Xi_{cc}^{P*}) = M + \Delta M^* + \Delta M, \ M (\Xi_{cc}^*) = M + \Delta M^*$. We suppose that two peaks can be distinguished in the invariant mass distribution for candidates to the first $P$-wave excitation of a diquark in a doubly charmed baryon. It seems that the decay width of $2S$-states exceeds the hyperfine splitting values, and therefore the transition $\Xi_{cc} (2S) \rightarrow \Xi_{cc} (1S) \pi$ will be represented by one wide peak in the invariant mass distribution.

4. Conclusions

In this study we calculate the relative yields of $S$- and $P$-wave excitations of doubly charmed baryons at LHC. The observation of narrow metastable $P$-states of $\Xi_{cc}$ in the decay mode $\Xi_{cc} \pi$ is rather challenging because of small yield of such states, which is about 3%. On the contrary, the structure corresponded to the decays $\Xi_{cc} (2S,3S) \rightarrow \Xi_{cc} \pi$ should be definitely observed in Run III. Indeed, about 50% of $\Xi_{cc}^{++}$ baryons come from $S$-wave excitations. Therefore from 300 $\Xi_{cc}^{++}$ observed at LHCb about 60 baryons are the products of decays with charged
pion $\Xi^+_c (2S, 3S) \rightarrow \Xi^+_{cc} \pi^-$ and about 20 baryons come from the decays with charged kaon $\Omega^+_c (2S, 3S) \rightarrow \Xi^+_{cc} K^-$. This is why we think, that Run III with large luminosity will provide a great opportunity to observe excited $S$-wave states of $\Xi^+_{cc}$ and $\Omega^+_{cc}$ baryons.

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