Production of Excited States of Doubly Heavy Baryons at the Large Hadron Collider

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Abstract—The yields of excited states of doubly heavy baryons are estimated on the basis of the diquark-production model under the kinematic conditions of the LHC experiments. Prospects of their observations are discussed.

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1. INTRODUCTION

Problems of the production and decay of doubly heavy baryons have attracted the attention of researchers for more than two decades (see, for example, [1, 2]). Possibly, this attention is due to their very interesting structure. Since these hadrons consist of two heavy quarks and one light quark, it is quite natural to break them down into two subsystems: a compact doubly heavy diquark and a light quark. The color-antitriplet states of the doubly heavy diquark can be described on the basis of the same models as those are used to describe quarkonium states—for example, potential models. Since the spectroscopy of quarkonia that lie below the threshold for decay to open flavor is described fairly well, it can be hoped that diquark spectroscopy will be described satisfactorily. Under the assumption that the diquark in question is a compact color-antitriplet object, its interaction with a light quark can be described as quark–antiquark interaction. This simplifies significantly theoretical investigations of doubly heavy baryons and makes it possible to obtain detailed predictions for the properties of such systems (see, for example, [1–4]).

It should be noted that the spectroscopy of doubly heavy baryons can be studied not only in the quark–diquark approximation but also via directly solving the respective quantum three-body problem (see, for example, [5–10]). This is quite an important line of research, but it is noteworthy that, at the present time, there are no decisive arguments in support of the statement that the quantum three-body problem is a more correct approximation than the quark–diquark approximation. For example, lattice calculations favor so-called Y-shaped coupling, from which the quark–diquark approximation follows naturally. The fact that the heavy quark–light diquark interaction model works well in describing the spectroscopy of baryons featuring one heavy quark lends additional support to the quark–diquark model in the case of light hadrons.

In studying the spectroscopy of doubly heavy baryons, one can choose between the above two approaches, but, in studying the production of doubly heavy baryons, there is no such choice: for them, the only more or less consistent production model known to date relies on the assumption that the initially produced diquark goes over to a doubly heavy baryon. Clearly, the production of a heavy diquark closely resembles the associated production of quarkonium and a heavy quark. In either case, the production of two pairs of heavy quarks at the first stage is followed by the formation of a doubly heavy system. Yet, there is a significant distinction. As was shown in [11–14], the associated production of quarkonium involving a hidden flavor and a heavy quark receives a large contribution from the so-called mechanism of double parton scattering (DPS), in which quarkonium and the heavy quark accompanying it originate from different parton collisions. In contrast to what occurs in heavy-quarkonium production, where the DPS mechanism makes a commensurate contribution, this mechanism is suppressed in diquark production. The independent production of two pairs of heavy quarks prevents their coherent merger to a diquark. Therefore, we expect that the yields of the doubly...
heavy baryons $\Xi_{cc}$ and $\Xi_{bb}$ are substantially smaller than the yields of the associated production of respective quarkonia and heavy quarks.

Doubly heavy baryons have been studied theoretically for many years, but the first ever experimental observation of such a state was reported by the LHCb Collaboration quite recently; in 2017, a baryon featuring two charmed quarks, $\Xi_{cc}^+$, was found in the $\Lambda^+ K^- \pi^+ \pi^+$ decay mode [15]. This observation was already confirmed in the $\Xi_c^+ \pi^+$ mode [16]. The lifetime of this new state was also measured [17]. In the present study, we discuss prospects of further investigations into doubly heavy baryons. In particular, we estimate the yields of doubly heavy baryons involving an excited heavy diquark, which are known as $\rho$ excitations (see Fig. 1).

2. TECHNIQUE OF CALCULATIONS

Since the technique of calculations performed here was described in detail elsewhere [18], we give here only a brief account of it.

Within the quark–diquark model, it is natural to break down baryon production into two stages. At the first stage of the calculations, a doubly heavy diquark in a color-antitriplet state is produced perturbatively in a hard interaction. At the second stage, the doubly heavy diquark goes over to a baryon via a soft hadronization process (see, for example, [19–23]). As a rule, the hadronization process is considered within the fragmentation approach by analogy with the hadronization of a heavy quark to a heavy hadron.

As was indicated in [24], soft-gluon emission complicates the classification of levels of a heavy diquark formed by quarks of different flavor; therefore, we will consider below only $cc$ and $bb$ diquarks.

Under the assumption that the dependence of the production amplitude for four heavy quarks, $T_{Q_1 Q_2 Q_3 Q_4}$, on the 3-momentum $\mathbf{q}$ of a quark within the diquark is weak, the diquark-production amplitude can be expanded in a power series in $\mathbf{q}$ as

$$A \sim \int d^3 \mathbf{q} \Psi^*_{[Q_1 Q_2]a}(\mathbf{q}) \left\{ T_{Q_1 Q_2 Q_3 Q_4} \bigg|_{\mathbf{q}=0} + \mathbf{q} \frac{\partial}{\partial \mathbf{q}} T_{Q_1 Q_2 Q_3 Q_4} \bigg|_{\mathbf{q}=0} + \cdots \right\},$$

where $\Psi_{[Q_1 Q_2]a}(\mathbf{q})$ is the wave function for the diquark in the color-antitriplet state. The first term in the expansion in (1) makes a dominant contribution to the production of the $S$-wave diquark, while the second term dominates the production of the $P$-wave diquark.

The requirement that the wave function for the diquark formed by two identical quarks be antisymmetric constrains its spin: the $S$-wave diquark may only have a spin of unity, while the $P$-wave diquark may only have zero spin. The production amplitude for the $S$-wave diquark state then has the form

$$A^{Sz} = \frac{1}{\sqrt{4\pi}} R_S(0) \cdot T^{Sz}_{QQQQ} \bigg|_{\mathbf{q}=0},$$

where $s_z$ is the diquark-spin projection, $R_S(0)$ is the value of the radial wave function at the origin, and the production amplitude for the $P$-wave state of the diquark is given by

$$A^{lz} = i \sqrt{\frac{3}{4\pi}} R_P(0) \cdot \{ \mathcal{L}^{lz} T_{QQQQ} \} \bigg|_{\mathbf{q}=0}. \tag{3}$$

Here, $l_z$ is the projection of the diquark orbital angular momentum, $R_P(0)$ is the derivative of the radial wave function at the origin, and $\mathcal{L}^{lz}$ is a differential operator of the form

$$\mathcal{L}^{lz} = \left\{ \begin{array}{l} \mathcal{L}^{-1} = \frac{1}{\sqrt{2}} \left( \frac{\partial}{\partial q_x} + i \frac{\partial}{\partial q_y} \right) \\ \mathcal{L}^0 = \frac{\partial}{\partial q_z} \\ \mathcal{L}^{+1} = -\frac{1}{\sqrt{2}} \left( \frac{\partial}{\partial q_x} - i \frac{\partial}{\partial q_y} \right) \end{array} \right. \tag{4}$$

The product color-antitriplet state should undergo hadronization, forming a baryon. The light quark of effective mass $m_q$ in the baryon of mass $M$ carries away about $m_q/M$ of the whole baryon transverse momentum, whence it follows that, under the LHCb kinematical conditions, this quark always exists in a quark sea. Therefore, it is natural to assume that the doubly heavy baryon undergoes hadronization upon picking up one of the light quarks, $u, d, \text{or } s$, in the same proportion of $1 : 1 : 0.26$ as the $b$ quark [25]. We also assume that it undergoes hadronization with a probability of unity. The last assumption is a guess to a considerable extent, since the diquark carries a color charge and, hence, interacts strongly with its environment, and this may lead to diquark dissociation.
Table 1. Wave functions for the doubly charmed diquark and its masses [26] along with the cross sections and relative yields for different states of the $cc$ diquark

| State | Wave function | Diquark mass | Relative yield | Cross section |
|-------|--------------|--------------|----------------|--------------|
|       | $|R(0)|$, GeV$^{3/2}$ | $m$, GeV | $r^*$, % | $\sigma$, nb |
| $1S$  | 0.566        | 3.20         | 49–52          | 120–170      |
| $2S$  | 0.540        | 3.50         | 26–27          | 60–90        |
| $3S$  | 0.542        | 3.70         | 18–20          | 40–70        |

On the other hand, we can assume that the diquark undergoes hadronization according to the fragmentation model by analogy with a heavy meson. Within this model, the diquark energy loss is described in terms of the fragmentation function, which is independent of the process. For heavy mesons, the form of fragmentation function can be found on the basis of experimental data on $e^+e^-$ annihilation, but, for a doubly heavy diquark, it is unknown. However, there are reasons to believe that the shape of this function is quite sharp even for the $cc$ diquark because of its relatively high mass.

3. PRODUCTION OF DOUBLY CHARMED BARYONS WITH EXCITED HEAVY DIQUARK AND PROSPECTS OF THEIR OBSERVATION

In order to estimate the cross sections for doubly charmed baryons and their yields in hadron–hadron interactions, we have used the wave functions proposed in [26] and the CTEQ parton functions [27].

The calculations were performed for the kinematical conditions of the LHCb detector: $2 < \eta < 4.5$ and $p_T < 10$ GeV at the collision energy of $\sqrt{s} = 13$ TeV for scales in the range from $E_T/2$ to $2E_T$. From our estimations, it follows that the relative yields of baryons containing a doubly charmed diquark in the $2S$ and $3S$ states are about 50% of the total yield, while the $P$-wave diquark states contribute only 3% to 5% (see Table 1 and Fig. 2). The estimates that we obtained show that the relative contribution of excited states grows slowly with increasing transverse momentum. However, this does not mean that searches for excited states at high transverse momenta would be advisable, since the absolute yields are higher at low momenta [18].

Having obtained an estimate of the yield of excited baryons, we will now discuss their decays.

Those excited states of doubly charmed baryons that lie below the threshold for decay to $\Lambda_c D$ undergo decay to the ground state. Wherever this is kinematically possible, the hadronic mode is dominant: the predicted electromagnetic-transitions widths [28–30] are at least two orders of magnitude smaller than the predicted hadronic-transition widths [30–35].

Since the quark–diquark model of doubly heavy baryons makes it possible to study individually the excitations of the light degree of freedom and the excitations of the heavy diquark, the transitions between different states of doubly heavy baryons can be partitioned within this approach to transitions associated with a change in the light-quark state and transitions associated with a change in the diquark state.

For $\Lambda$ excitations of doubly charmed baryons, all theoretical groups [30–33] predict a broad decay width of 40 to 300 MeV, but, for $\rho$ excitations addressed in the present study, the predictions of various research group contradict one another. According to the predictions made in [34], for example, the widths of doubly charmed baryons involving the first radial diquark excitation and those for the excitation of the light degree of freedom are commensurate, 4)

\[
\Gamma [\Xi_{cc}(2S1s(1/2)) \to \Xi_{cc}(1S1s)] \sim 50 \text{ MeV},
\]

\[
\Gamma [\Xi_{cc}(2S1s(3/2)) \to \Xi_{cc}(1S1s)] \sim 400 \text{ MeV},
\]

but this contradicts the results of Eakins and Roberts [36], who predicted, for these quantities, values smaller than 0.5 MeV.

Doubly charmed baryons featuring the $P$-wave state of the heavy diquark are of great interest in the family of doubly charmed baryons. As was shown

4) Hereafter, we use the commonly accepted notation where a number and an uppercase letter denote the heavy-diquark orbital state, a number and a lowercase letter denote the light-quark orbital state, and a number in parentheses is the total angular momentum of the baryon.
in [37], their decays should be accompanied by a simultaneous change in the diquark spin and angular momentum, with the result that the respective width is suppressed by the factor $\Lambda_{QCD}^2/m_c^2$. Thus, doubly charmed baryons in which the heavy diquark is in the $P$-wave state are metastable. This conclusion is confirmed in part by the results obtained in [35], where the widths of the $\Xi_{cc}(1P)$ states are estimated as

$$\begin{align*}
\Gamma[\Xi_{cc}(1P1s(3/2)) \rightarrow \Xi_{cc}(1S1s(3/2))\pi] &= 112\lambda_{3/2}^2 \text{ MeV}, \\
\Gamma[\Xi_{cc}(1P1s(1/2)) \rightarrow \Xi_{cc}(1S1s(1/2))\pi] &= 111\lambda_{1/2}^2 \text{ MeV},
\end{align*}$$

(5)

where $\lambda_{3/2},\lambda_{1/2} \sim \Lambda_{QCD}/m_c$. Obviously, these states are indeed metastable at small values of $\lambda_{1/2}$ and $\lambda_{3/2}$.

The charge-exchange decays of such $P$-wave states can be used to discover them under the conditions of experiments at the LHC. The decays $\Xi_{cc}^{++}(1P1s(1/2)) \rightarrow \Xi_{cc}^{+}(1S1s(1/2))\pi^+$ and $\Xi_{cc}^{+}(1P1s(1/2)) \rightarrow \Xi_{cc}^{++}(1S1s(1/2))\pi^-$ can be completely reconstructed. The decays $\Xi_{cc}^{++}(1P1s(1/2)) \rightarrow \Xi_{cc}^{+}(1S1s(3/2))\pi^+ \rightarrow [\Xi_{cc}^{+}(1S1s(1/2))\pi^+ \rightarrow \Xi_{cc}^{+}(1S1s(3/2))\pi^- \rightarrow [\Xi_{cc}^{+}(1S1s(3/2))\gamma]\pi^-$ can be reconstructed apart from a photon since the detection efficiency is low for the respective soft photon. Nevertheless, the peak corresponding to $\Xi_{cc}(1P1s(3/2))$ in the distribution of the $\Xi_{cc}\pi$ invariant mass can be distinguished since it is shifted by the mass splitting of the doublet $1S1s$ and is characterized by an additional broadening given by

$$\Delta M \approx 2\Delta M^S \sqrt{(\Delta M^{PS}/M)^2 - (m_{\pi}/M)^2} \sim 10 \text{ MeV},$$

where $M$ is the ground-state mass; $m_{\pi}$ is the pion mass; $\Delta M^S = M(\Xi_{cc}(1S1s(3/2))) - M(\Xi_{cc}(1S1s(1/2)))$; and $\Delta M^{PS}$ is the mass difference between the $1P1s(3/2)$ and $1S1s(3/2)$ states—that is, $\Delta M^{PS} = M(\Xi_{cc}(1P1s(3/2))) - M(\Xi_{cc}(1S1s(3/2)))$. Figure 3 illustrates the possible shape of peaks in the invariant-mass distribution of candidates for the first $P$-wave excited state of the diquark in the doubly charmed baryon. It is noteworthy that the transition within the $1S1s$ doublet may proceed only via photon emission since the mass splitting $\Delta M^S$ is about 100 to 130 MeV [26, 38–40]—that is, it is less than the pion mass.

In the $\Omega_{cc}$ spectrum, analogous one-pion transitions violate isospin symmetry, whence it follows that, if kinematically possible, $\Omega_{cc}$ excitations decay to the ground state of $\Xi_{cc}$ via kaon emission. The first $P$-wave diquark excitation in $\Omega_{cc}$ is an individual case. Here, one-pion transitions are suppressed by three order of magnitude because of isospin-symmetry violation [31], while one-kaon transitions are forbidden kinematically. As a result, the hadronic mode is
not dominant over the electromagnetic one for these states [28, 31].

In all probability, the decay widths of $2S$ states exceed hyperfine splitting $\Delta M^S$, with the result that a determination of the quantum numbers $J^P$ in the transition $\Xi_{cc}(2S) \to \Xi_{cc}(1S)\pi$ is impossible, so that this transition manifests itself as a broad peak in the invariant-mass distribution.

On the basis of the above estimates of the relative excited-baryon yields, we can roughly evaluate the experimental observed total yield of $\Xi_{cc}^{++}$ can be estimated as

$$N_{\text{tot}} \sim N_{\text{direct}(\Xi_{cc}^{++})}$$

$$+ \frac{1}{3} N(\Xi_{cc}^{++} \to \Xi_{cc}^{++}\pi^0) + \frac{2}{3} N(\Xi_{cc}^{++} \to \Xi_{cc}^{++}\pi^-)$$

$$+ \frac{1}{2} \cdot \frac{1}{2} N(\Omega_{cc}^{++} \to \Xi_{cc}^{++}K^-).$$

Here, the coefficients of $N(\Xi_{cc}^{++} \to \Xi_{cc}^{++}\pi^0)$ and $N(\Xi_{cc}^{++} \to \Xi_{cc}^{++}\pi^-)$ are determined by isospin counting, while the coefficient of $N(\Omega_{cc}^{++} \to \Xi_{cc}^{++}K^-)$ is determined by isospin counting and the idea that about half of the excited states $\Omega_{cc}^{++}$ may lie below the $\Xi_{cc}^{++}K^-$ threshold. Assuming that excited diquarks undergo hadronization upon picking up a light quark in the same proportion as unexcited ones—$u : d : s = 1 : 1 : 0.26$—one can conclude that, of $N_{\text{tot}} \approx 300$ detected $\Xi_{cc}^{++}$ particles, approximately $\frac{2}{3} \times 300 \approx 90$ baryons are products of $\Xi_{cc}^{++}$ decay, approximately $\frac{2}{3} \times 300 \approx 45$ ones are products of $\Omega_{cc}^{++}$ decay, and about $\frac{0.26}{2.26} \times 300 \approx 10$ ones originate from $\Omega_{cc}^{++}$ decay.

4. EXCITED DOUBLY BEAUTY BARYONS AND PROSPECTS OF THEIR OBSERVATION

It is noteworthy that prospects of observing even the ground state are still vague because of a very small production cross section for such baryons. For such a state to arise, the production of four beauty quarks is necessary, which leads to a strong suppression because of a small phase space at low gluon energies. At high energies, the cross section in the fragmentation mode is suppressed with respect to the cross section for $b$-quark production approximately in proportion to $|R(0)|^2/m_b^3$. Most probably, there is no DPS-induced enhancement in such processes. Nevertheless, the possibility of searches for such states is being discussed. For example, we would like to mention a very interesting study of Gershon and Poluektov [41], who consider the possibility of revealing $\Xi_{bb}$ by means of detecting $B_c$ mesons whose momentum is not directed to the primary interaction vertex; with a high probability, they are products of $\Xi_{bb}$ decay. Taking into account current interest in the problem of detecting $\Xi_{bb}$, we estimate here the relative yield of the $\Xi_{bb}$ baryon involving $S$- and $P$-wave diquark excitations.

By employing the mass values and wave functions obtained in [26, 42], we present our estimates of the cross sections for the relative yields of excited states (see Table 2 and Fig. 4). As follows from our estimates, the yield of the metastable $P$-wave states of doubly beauty baryons is suppressed to even a greater extent than the yield of the $P$-wave states of doubly charmed baryons and is found to be 2% of the total yield of doubly beauty baryons. At the same time, the contribution of $S$-wave states, which is about 60%, is somewhat greater than the contribution of the analogous states to the yield of doubly charmed baryons (about 50%).

Since the $bb$ diquark is more compact, the quark-diquark model is expected to describe the family of doubly beauty baryons more successfully than the family of doubly charmed baryons. The reason is that the corrections for the diquark size should be smaller in the former case [24]. It is also noteworthy that the states of the pseudostable baryons involving a scalar $P$-wave $bb$ diquark should be narrower than the analogous states involving a $cc$ diquark: the width of the former should be smaller approximately in proportion to $m_b^2/m_c^2$. This is confirmed by the values in (5).
Fig. 4. Relative yields of excited (a) S- and (b) P-wave states of the doubly beauty diquark versus the transverse momentum for different scales at the proton–proton interaction energy of $\sqrt{s} = 13$ TeV.

Table 2. Wave functions for the doubly beauty diquark and its masses [26, 42] along with the cross sections and relative yields for different states of the $bb$ diquark

| State | Wave function $|R(0)|$, GeV$^{3/2}$ | Diquark mass $m$, GeV | Relative yield $r^*$, % | Cross section $\sigma$, pb |
|-------|---------------------------------|-----------------|-----------------|----------------------|
| $1S$  | 1.107                           | 9.8             | 36–37           | 320–670              |
| $2S$  | 0.969                           | 10.0            | 24–25           | 210–450              |
| $3S$  | 0.927                           | 10.2            | 19–20           | 170–360              |
| $4S$  | 0.906                           | 10.3            | 17–18           | 150–320              |
| $1P$  | 0.387                           | 9.9             | 0.3             | 3–6                  |
| $2P$  | 0.484                           | 10.1            | 0.4             | 4–8                  |
| $3P$  | 0.551                           | 10.3            | 0.5             | 4–9                  |
| $4P$  | 0.605                           | 10.4            | 0.5             | 4–9                  |

5. CONCLUSIONS

We have estimated the relative yields of doubly charmed and doubly beauty baryons containing an excited heavy diquark. In either case, excitations involving the $S$-wave diquark state account for half of the total yield of such doubly heavy baryons, while excitations involving the $P$-wave diquark state contribute only a few percent to the total yield. Our calculations have shown that the search for $S$-wave diquark excitations of doubly charmed baryons is within the potential of the LHCb experiment. Searches for $P$-wave states of doubly charmed baryons is a much more difficult challenge. Prospects of detecting excitations of $\Xi_{bb}$ baryons in experiments at the LHC are questionable at the present time.

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