Identifying the $\Xi^0_c$ baryons observed by LHCb as P-wave $\Xi^+_c$ baryons

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We systematically study mass spectra and decay properties of P-wave $\Xi^0_c$ baryons of the SU(3) flavor $6_F$, using the methods of QCD sum rules and light-cone sum rules within the framework of heavy quark effective theory. Our results suggest that the three excited $\Xi^0_c$ baryons recently observed by LHCb can be well explained as P-wave $\Xi^+_c$ baryons: the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ are partner states of $J^P = 1/2^-$ and $3/2^-$ respectively, both of which contain one $\lambda$-mode orbital excitation; the $\Xi_c(2965)^0$ has $J^P = 3/2^-$, and also contains one $\lambda$-mode orbital excitation. More partner states and more decay channels are extracted (summarized in Table II) for future experimental searches.

Keywords: excited heavy baryons, heavy quark effective theory, QCD sum rules, light-cone sum rules

Introduction —– The light quarks and gluons circle around the nearly static heavy quark inside the heavy baryon. This system is the QCD analogue of the hydrogen, but bounded by the strong interaction [1–3]. In three recent LHCb experiments [4–6] its spectra are found to have beautiful fine structures: five excited $\Omega^0_b$ baryons were observed in the experiment [4]; four excited $\Omega^+_b$ baryons were observed in the experiment [5]; in the very recent experiment [6] three excited $\Xi^0_c$ baryons were observed simultaneously in the $\Lambda^+_c K^-$ mass spectrum, whose parameters were measured to be:

$$\Xi_c(2923)^0 : M = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \text{ MeV},$$
$$\Gamma = 7.1 \pm 0.8 \pm 1.8 \text{ MeV},$$

$$\Xi_c(2939)^0 : M = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14 \text{ MeV},$$
$$\Gamma = 10.2 \pm 0.8 \pm 1.1 \text{ MeV},$$

$$\Xi_c(2965)^0 : M = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \text{ MeV},$$
$$\Gamma = 14.1 \pm 0.9 \pm 1.3 \text{ MeV}.\quad (3)$$

These excited $\Omega^0_b/\Omega^+_b/\Xi^0_c$ baryons are good candidates of P-wave charmed and bottom baryons, whose observations have proved the rich internal structure of (heavy) hadrons [7–9].

The LHCb Collaboration [6] further pointed out that the $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons are probably the sub-structures of $\Xi_c(2930)^0$ [10, 11], while the $\Xi_c(2965)^0$ and $\Xi_c(2970)^0$ [12] might be different states. Many phenomenological methods and models have been applied to understand the $\Xi_c(2930)^0$ and $\Xi_c(2970)^0$ previously observed by BaBar [10] and Belle [12], such as various quark models [13–24], various molecular explanations [25–29], the chiral perturbation theory [30, 31], Lattice QCD [32, 33], and QCD sum rules [34–40], etc. We refer to the reviews [9, 41–43] and references therein for detailed discussions.

We have systematically studied mass spectra and decay properties of P-wave heavy baryons in Refs. [44–47] using the methods of QCD sum rules [48, 49] and light-cone sum rules [50–54] within the framework of heavy quark effective theory (HQET) [55–57]. The results were combined in Ref. [47] so that a rather complete study within HQET was performed on both mass spectra and decay properties of P-wave bottom baryons. There we predicted four $\Xi^+_b$ baryons, three of which have finite and limited widths, while the rest one has a (nearly) zero width:

$$[\Xi^+_b(1/2^-), 1, 1, \lambda] : M = 6.21 \pm 0.11 \text{ GeV},$$
$$\Gamma = 4.7 \pm 5.8 \pm 3.3 \text{ MeV},$$

$$[\Xi^+_b(3/2^-), 1, 1, \lambda] : M = 6.22 \pm 0.11 \text{ GeV},$$
$$\Gamma = 1.8 \pm 1.1 \pm 1.0 \text{ MeV},$$

$$[\Xi^+_b(3/2^-), 2, 1, \lambda] : M = 6.23 \pm 0.15 \text{ GeV},$$
$$\Gamma = 27.3 \pm 28.5 \pm 14.2 \text{ MeV},$$

$$[\Xi^+_b(5/2^-), 2, 1, \lambda] : M = 6.24 \pm 0.14 \text{ MeV},$$
$$\Gamma \sim 0 \text{ MeV},$$

(7) with the mass splittings:

$$M[\Xi^+_b(3/2^-), 1, 1, \lambda] - M[\Xi^+_b(1/2^-), 1, 1, \lambda] = 7 \pm 2 \text{ MeV},$$

$$M[\Xi^+_b(5/2^-), 2, 1, \lambda] - M[\Xi^+_b(3/2^-), 2, 1, \lambda] = 11 \pm 5 \text{ MeV}.\quad (8)$$

The above notations will be explained later, and we refer to Ref. [47] for their detailed decay channels.

From our previous results [47], we might think that the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ are just the charmed partners of the $[\Xi^+_b(1/2^-), 1, 1, \lambda]$, $[\Xi^+_b(3/2^-), 1, 1, \lambda]$, and $[\Xi^+_b(3/2^-), 2, 1, \lambda]$, respectively. To verify this, in this letter we follow the same approach used in Refs. [44–47] to study the above excited $\Xi^0_c$ baryons recently observed by LHCb [5]. We shall find that all of them can be interpreted as P-wave $\Xi^+_c$ baryons of the SU(3) flavor $6_F$, so that both their mass spectra and decay properties can be well explained.

Categorization of P-wave $\Xi^+_c$ baryons within HQET —–

We follow Ref. [14] and use the same notations to describe P-wave $\Xi^+_c$ baryons of the SU(3) flavor $6_F$. Each baryon consists of one charm quark and two light quarks, and contains one orbital excitation, which can be either
between the two light quarks \((l_ρ = 1)\) or between the charm quark and the two-light-quark system \((l_λ = 1)\). Hence, there are \(ρ\)-mode excited \(Ξ_c^\prime\) baryons \((l_ρ = 1 \text{ and } l_λ = 0)\) and \(λ\)-mode ones \((l_ρ = 0 \text{ and } l_λ = 1)\). Together with the color, flavor, and spin degrees of freedom, its internal structures are:

- **Color structure of the two light quarks** is antisymmetric, that is the color \(3C\).
- **Flavor structure of the two light quarks** is symmetric, that is the \(SU(3)\) flavor \(6_F\).
- **Spin structure of the two light quarks** can be either antisymmetric \((s_l = s_{qq} = 0)\) or symmetric \((s_l = 1)\).
- **Orbital structure of the two light quarks** can be either antisymmetric \((l_ρ = 1)\) or symmetric \((l_ρ = 0)\).

Considering that the total structure of the two light quarks is antisymmetric due to the Pauli principle, we can categorize P-wave \(Ξ_c^\prime\) baryons into four multiplets, denoted as \([6_F, j_λ, s_l, ρ/λ]\). We show them in Fig. 1, where \(j_λ\) denotes the total angular momentum of the light components \((j_λ = s_l \otimes l_ρ \otimes l_λ)\). Every multiplet contains one or two \(Ξ_c^\prime\) baryons, whose total angular momenta are \(j = j_λ \otimes s_c = |j_λ \pm 1/2|\), with \(s_c\) the charm quark spin.

**Mass spectra from QCD sum rules within HQET**—

We have systematically studied mass spectra of P-wave charmed baryons in Ref. [44] using QCD sum rules within HQET. In this method we calculate the baryon mass through

\[
m_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ} = m_c + \Lambda_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ} + \delta m_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ},
\]

where \(m_c\) is the charm quark mass, \(\Lambda_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ} = \Lambda_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ} - \Lambda_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ} = \Lambda_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ}\) is extracted from the mass sum rules at the leading order, and \(\delta m_{Ξ'(j^{P'}).j_λ,s_l,ρ/λ}\) is extracted from the mass sum rules at the \(O(1/m_c)\) order.

Eq. (9) tells that the \(Ξ_c^\prime\) mass depends significantly on the charm quark mass. Hence, there exists considerable (theoretical) uncertainty in our results for absolute values of baryon masses, and we can not distinguish the three excited \(Ξ_c^\prime\) baryons observed by LHCb [6] only by using their mass spectra. However, the mass splittings within the same multiplets are produced at the \(O(1/m_c)\) order with much less uncertainty, giving more useful information.

We can extract even more useful information from decay properties of P-wave \(Ξ_c^\prime\) baryons. To do this we first fine-tune one of the two free parameters in mass sum rules, the threshold value \(ω_{ci}\), in order to better describe the LHCb experiment [4, 58]. We summarize the obtained results in Table I, together with the parameters that are necessary to calculate decay widths through light-cone sum rules.

**Decay widths from light-cone sum rules within HQET**—

We have systematically studied decay properties of P-wave heavy baryons in Refs. [45–47] using light-cone sum rules within HQET, and the results are combined in Ref. [47] to study P-wave bottom baryons. In the present study we replace the bottom quark by the charm quark, and redo all the calculations. The obtained results are summarized in Table II, where we have investigated all the possible \(S\)-wave and \(D\)-wave decays of P-wave \(Ξ_c^\prime\) baryons into ground-state charmed baryons and light pseudoscalar mesons.

During the calculations, we have used the following mass values:

- For the \([6_F(Ξ_c^\prime), 1, 0, ρ]\) doublet, we use the following mass values taken from their mass sum rules:
  \[
  M_{[Ξ_c^\prime(1/3^-),1,0,ρ]} = 2.89^{+0.15}_{-0.14} \text{ GeV}, \quad M_{[Ξ_c^\prime(3/2^-),1,0,ρ]} = 2.90^{+0.15}_{-0.13} \text{ GeV}.
  \]

- For the \([6_F(Ξ_c^\prime), 0, 1, λ]\) singlet, we use the following mass value taken from its mass sum rules:
  \[
  M_{[Ξ_c^\prime(1/2^-),0,1,λ]} = 3.00^{+0.16}_{-0.13} \text{ GeV}.
  \]

- For the \([6_F(Ξ_c^\prime), 1, 1, λ]\) doublet, we use the following mass values taken from the LHCb experiment [6]:
  \[
  M_{[Ξ_c^\prime(1/2^-),1,1,λ]} = M_{Ξ_c^\prime(2923)^0} = 2923.04 \text{ GeV}, \quad M_{[Ξ_c^\prime(3/2^-),1,1,λ]} = M_{Ξ_c^\prime(2939)^0} = 2938.55 \text{ GeV}.
  \]

- For the \([6_F(Ξ_c^\prime), 2, 1, λ]\) doublet, we use the following mass values, taken from the LHCb experiment [6] as well as their mass sum rules:
  \[
  M_{[Ξ_c^\prime(3/2^-),2,1,λ]} = M_{Ξ_c^\prime(2965)^0} = 2964.88 \text{ MeV}, \quad M_{[Ξ_c^\prime(5/2^-),2,1,λ]} = M_{Ξ_c^\prime(3/2^-),2,1,λ} + 64 \text{ MeV}.
  \]
TABLE I: Mass spectra of $P$-wave $\Xi_c'$ baryons of the $SU(3)$ flavor $6_F$, evaluated using QCD sum rules within HQET. Here we also list the parameters that are necessary to calculate decay widths through light-cone sum rules.

| Multiplets | $\omega_c$ (GeV) | Working region | $\mathcal{M}$ (GeV) | $\Xi_c'$ Mass | Difference (MeV) | $f$ (GeV$^4$) |
|------------|------------------|----------------|---------------------|---------------|----------------|--------------|
| $[6_F(\Xi_c'), 1, 0, \rho]$ | 1.88 | $0.26 < T < 0.34$ | $1.37^{+0.12}_{-0.08}$ | $\Xi_c'(1/2^-)$ | $2.89^{+0.15}_{-0.13}$ | $13^{+6}_{-5}$ | $0.060^{+0.017}_{-0.011}$ |
| | | | | $\Xi_c'(3/2^-)$ | $2.90^{+0.15}_{-0.13}$ | | $0.029^{+0.008}_{-0.005}$ |
| $[6_F(\Xi_c'), 0, 1, \lambda]$ | 1.68 | $0.27 < T < 0.30$ | $1.25^{+0.10}_{-0.08}$ | $\Xi_c'(1/2^-)$ | $3.00^{+0.15}_{-0.13}$ | $-$ | $0.050^{+0.013}_{-0.010}$ |
| $[6_F(\Xi_c'), 1, 1, \lambda]$ | 1.75 | $T = 0.35$ | $1.17^{+0.09}_{-0.09}$ | $\Xi_c'(1/2^-)$ | $2.96^{+0.13}_{-0.12}$ | $38^{+15}_{-14}$ | $0.044^{+0.009}_{-0.008}$ |
| | | | | $\Xi_c'(3/2^-)$ | $3.00^{+0.15}_{-0.13}$ | | $0.021^{+0.004}_{-0.004}$ |
| $[6_F(\Xi_c'), 2, 1, \lambda]$ | 1.75 | $0.27 < T < 0.32$ | $1.26^{+0.15}_{-0.09}$ | $\Xi_c'(3/2^-)$ | $3.00^{+0.15}_{-0.15}$ | | $0.061^{+0.021}_{-0.012}$ |
| | | | | $\Xi_c'(5/2^-)$ | $3.06^{+0.24}_{-0.14}$ | | $0.026^{+0.009}_{-0.005}$ |

The reasons why we selected these mass values will be discussed as follows.

Understanding the three $\Xi_c^0$ baryons within HQET—
In the present study we have investigated $P$-wave $\Xi_c'$ baryons of the $SU(3)$ flavor $6_F$ by systematically studying their mass spectra and decay properties using the methods of QCD sum rules and light-cone sum rules within the framework of heavy quark effective theory. The obtained results are summarized in Table II, from which we can well understand the three excited $\Xi_c^0$ baryons recently observed by LHCb [6] as $P$-wave $\Xi_c'$ baryons of the $SU(3)$ flavor $6_F$.

There can be as many as seven $P$-wave $\Xi_c'$ baryons,
belonging to four multiplets:
\[
\begin{align*}
\Xi_c'(1/2^-), & \  \Xi_c'(3/2^-) \in [6_F, 1, 0, \rho], \\
\Xi_c'(1/2^-) & \in [6_F, 0, 1, \lambda], \\
\Xi_c'(1/2^-), & \  \Xi_c'(3/2^-) \in [6_F, 1, 1, \lambda], \\
\Xi_c'(3/2^-), & \  \Xi_c'(5/2^-) \in [6_F, 2, 1, \lambda].
\end{align*}
\]

Our results suggest:

- The width of \(\Xi_c'(1/2^-), 0, 1, \lambda\) is too large for it to be observed in experiments.
- The \(\Xi_c(2923)^0\) and \(\Xi_c(2939)^0\) can be interpreted as the \(P\)-wave \(\Xi_c'\) baryons of \(J^P = 1/2^-\) and \(3/2^-\) respectively, both of which belong to the \([6_F(\Xi_c'), 1, 1, \lambda]\) doublet.
- The \(\Xi_c(2965)^0/\Xi_c(2970)^0\) can be interpreted as the \(P\)-wave \(\Xi_c'\) baryon of \(J^P = 3/2^-\), belonging to the \([6_F(\Xi_c'), 2, 1, \lambda]\) doublet. Its partner state of \(J^P = 5/2^-\) is quite narrow, with mass \(642^{+29}_{-27}\) MeV larger.
- The widths of \(\Xi_c'(1/2^-)\) and \(\Xi_c'(3/2^-)\) belonging to the \([6_F(\Xi_c), 1, 0, \rho]\) doublet are evaluated to be about 118 MeV and 61 MeV respectively, making them not so easy to be observed. We notice that there is “an additional component” observed by LHCb in the energy region around 2900 MeV \([6]\), which may be due to these two states.
- The HQET is an effective theory, which works better for bottom baryons but worse for charmed baryons. This suggests that the three \(J = 1/2^- \Xi_c\) baryons can mix together and the three \(J = 3/2^-\) ones can also mix together, making it possible to observe all of them in the \(\Lambda_c K\) invariant mass spectrum.
- Especially, the mixing of the two \(\Xi_c'(3/2^-)\) baryons belonging to the \([6_F, 1, 1, \lambda]\) and \([6_F, 2, 1, \lambda]\) doublets can mediate their widths as well as decrease the mass splitting within the \([6_F, 1, 1, \lambda]\) doublet, which causes some discrepancies between our theoretical results and the LHCb measurements \([6]\).

The above conclusions are obtained by combining our systematical studies on mass spectra, mass splittings within the same multiplets, and decay properties of \(P\)-wave \(\Xi_c'\) baryons. Moreover, we have taken into account the five excited \(\Omega_c^0\) and four excited \(\Omega_c^-\) baryons observed by LHCb \([4, 5]\), whose correspondences may be \([59]\):

\[
\begin{align*}
[6_F(7/2^-), 1, 0, \rho] & : \Xi_c'(?/2^-) \sim \Omega_c^0(3000) \sim \Omega_c^-(6316), \\
[6_F(1/2^-), 1, 1, \lambda] & \sim \Omega_c^0(2923) \sim \Omega_c^0(3050) \sim \Omega_c^-(6330), \\
[6_F(3/2^-), 1, 1, \lambda] \sim \Omega_c^0(2939) \sim \Omega_c^0(3066) \sim \Omega_c^-(6340), \\
[6_F(3/2^-), 2, 1, \lambda] \sim \Xi_c'(2965) \sim \Omega_c^0(3090) \sim \Omega_c^-(6350), \\
[6_F(5/2^-), 2, 1, \lambda] \sim \Xi_c'(3119) \sim \Omega_c^0(5/2^-). \end{align*}
\]

We shall detailedly discuss this in our future work \([58]\).

To end this paper, we note that the conclusions of the present study are just possible explanations, and there exist some other possibilities for the three excited \(\Xi_c\) baryons observed by LHCb \([6]\). Further experimental and theoretical studies are still demanded to fully understand them. Anyway, the beautiful fine structures of the excited singly heavy baryons observed in the three LHCb experiments \([4-6]\) have proved the rich internal structure of (heavy) hadrons, and their relevant studies are significantly improving our knowledge of the strong interaction.

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