Excited $\Omega_b$ baryons and fine structure of strong interaction

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The heavy baryon system bound by the strong interaction has a rich internal structure, so its mass spectra can have the fine structure similar to the line spectra of atom bound by the electromagnetic interaction. We systematically study the internal structure of $P$-wave $\Omega_b$ baryons, and calculate their mass spectra and strong decay properties. Our results suggest that all the four excited $\Omega_b$ baryons recently discovered by LHCb can be well explained as $P$-wave $\Omega_b$ baryons, and their beautiful fine structure is directly related to the rich internal structure of $P$-wave $\Omega_b$ baryons.

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

Introduction — The electromagnetic interaction holds the electrons and protons together inside a single atom, leading to the gross, fine, and hyperfine structures of the line spectra. The strong interaction occurring between quarks and gluons is similar in some aspects, and it is interesting to investigate whether the hadron spectra also have the fine structure. An ideal platform to study this is the heavy baryon system containing one charm or bottom quark, which is interesting in a theoretical point of view [1–3]: the light quarks and gluons circle around the nearly static heavy quark, so that the whole system behaves as the QCD analogue of the hydrogen bounded by the electromagnetic interaction. This system has a rich internal structure, so its mass spectra can have the fine structure similar to hydrogen spectra [4–7].

In the past years important progress has been made in this field, and many heavy baryons were observed in experiments [4, 8–12]. Especially, in 2017 the LHCb Collaboration discovered as many as five excited $\Omega_c$ states, $\Omega_c^+(3000), \Omega_c^+(3050), \Omega_c^0(3066), \Omega_c^0(3090)$, and $\Omega_c^0(3119)$, simultaneously in the $\Xi_c^+K^−$ mass spectrum [8]. Very recently, they further discovered four excited $\Omega_b$ states simultaneously in the $\Xi_b^0K^−$ mass spectrum [12]:

\[
\Omega_b(6316)^− : M = 6315.64 ± 0.31 ± 0.07 ± 0.50 \text{MeV}, \quad \Gamma < 2.8 \text{MeV}, \quad (1)
\]

\[
\Omega_b(6330)^− : M = 6330.30 ± 0.28 ± 0.07 ± 0.50 \text{MeV}, \quad \Gamma < 3.1 \text{MeV}, \quad (2)
\]

\[
\Omega_b(6340)^− : M = 6339.71 ± 0.26 ± 0.05 ± 0.50 \text{MeV}, \quad \Gamma < 1.5 \text{MeV}, \quad (3)
\]

\[
\Omega_b(6350)^− : M = 6349.88 ± 0.35 ± 0.05 ± 0.50 \text{MeV}, \quad \Gamma = 1.47^{+1.0}_{−0.7} ± 0.1 \text{MeV}. \quad (4)
\]

These excited $\Omega_c$ and $\Omega_b$ states are good candidates of $P$-wave charmed and bottom baryons. To understand them, many phenomenological methods and models have been applied, such as various quark models [13–24], the chiral perturbation theory [25, 26], the molecular model [27–34], Lattice QCD [35, 36], and QCD sum rules [37–49], etc. We refer to reviews [7, 50–52] and references therein for their recent progress.

In Refs. [45, 46] we systematically studied mass spectra of $P$-wave heavy baryons using QCD sum rules [53, 54] within the framework of heavy quark effective theory (HQET) [55–57]. Later in Refs. [47–49] we systematically studied their $S$-wave decays into ground-state heavy baryons together with light pseudoscalar and vector mesons, using light-cone sum rules [58–62] within HQET. Recently, we have applied the same method to systematically study their $D$-wave decays into ground-state heavy baryons and light pseudoscalar mesons [63]. Hence, we have performed a rather complete study on both the mass spectra and strong decay properties of $P$-wave heavy baryons within the framework of HQET.

In this letter we shall apply these sum rule results to study the four excited $\Omega_b$ baryons recently observed by LHCb [12]. We shall find that all of them can be well interpreted as $P$-wave $\Omega_b$ baryons, so that both their mass spectra and decay properties can be well explained. Especially, their beautiful fine structure can be well explained in the framework of HQET, that is directly related to the rich internal structure of $P$-wave $\Omega_b$ baryons.

A global picture from the heavy quark effective theory — First let us briefly introduce our notations. A $P$-wave $\Omega_b$ baryon consists of one bottom quark and two strange quarks. Its orbital excitation can be either between the two strange quarks ($l_\rho = 1$) or between the bottom quark and the two-strange-quark system ($l_\lambda = 1$), so there are $\rho$-mode excited $\Omega_b$ baryons ($l_\rho = 1$ and $l_\lambda = 0$) and $\lambda$-mode ones ($l_\rho = 0$ and $l_\lambda = 1$). Altogether its internal symmetries are as follows:

- Color structure of the two strange quarks is anti-symmetric ($\mathbf{3}_C$).
- Flavor structure of the two strange quarks is sym-
metric, that is the $SU(3)$ flavor $6_F$.

- Spin structure of the two strange quarks is either antisymmetric ($s_1 = 0$) or symmetric ($s_1 = 1$).

- Orbital structure of the two strange quarks is either antisymmetric ($l_p = 1$) or symmetric ($l_p = 0$).

- Totally, the two strange quarks should be antisymmetric due to the Pauli principle.

Accordingly, we can categorize $P$-wave $\Omega_b$ baryons into four multiplets, as shown in Fig. 1. We denote them as $[6_F, j_l, s_l, \rho/\lambda]$, where $j_l$ is the total angular momentum of the light components ($j_l = l_b \otimes l_p \otimes s_b$). Each multiplet contains one or two $\Omega_b$ baryons, denoted as $[\Omega_b(j^P), j_l, s_l, \rho/\lambda]$, where $j^P$ are their total spin-parity quantum numbers ($j = j_l \otimes s_b = [j_l \pm 1/2]$ with $s_b$ the bottom quark spin). Note that there are other four multiplets with the $SU(3)$ flavor $\bar{3}_F$, and we refer to Refs. [14, 45, 46] for more discussions.

**Mass spectrum from QCD sum rules within HQET**

We have systematically constructed all the $P$-wave heavy baryon interpolating fields in Ref. [45], and applied them to study the mass spectrum of $P$-wave bottom baryons in Refs. [46, 48, 49] using the method of QCD sum rules within HQET. In this framework the $\Omega_b$ baryon belonging to the multiplet $[F, j_l, s_l, \rho/\lambda]$ has the mass:

$$m_{\Omega_b(j^P), j_l, s_l, \rho/\lambda} = m_b + \Delta m_{\Omega_b(j^P), j_l, s_l, \rho/\lambda},$$

where $m_b$ is the bottom quark mass, $\Delta m_{\Omega_b(j^P), j_l, s_l, \rho/\lambda}$ is the sum rule result evaluated at the leading order, and $\Delta m_{\Omega_b(j^P), j_l, s_l, \rho/\lambda}$ is the sum rule result evaluated at the $O(1/m_b)$ order.

We clearly see from Eq. (5) that the $\Omega_b$ mass depends significantly (almost linearly) on the bottom quark mass, for which we used the $1S$ mass $m_b = 4.66^{+0.04}_{-0.03}$ GeV [64] in Ref. [46], while the pole mass $m_b = 4.78 \pm 0.06$ GeV [4] and the $\overline{\text{MS}}$ mass $m_b = 4.18^{+0.04}_{-0.03}$ GeV [4] are used in some other QCD sum rule studies. This suggests that there is considerable theoretical uncertainty in our results for absolute values of the masses, which prevents us from touching the nature of the four excited $\Omega_b$ baryons observed by LHCb [12]. However, the mass differences within the same doublet do not depend much on the bottom quark mass, so they are produced quite well with much less theoretical uncertainty and give more useful information.

Besides, we can extract even (much) more useful information from strong decay properties of $P$-wave $\Omega_b$ baryons. Before doing this, we slightly modify one of the free parameters in QCD sum rules, the threshold value $\omega_c$, to get a better description of the four excited $\Omega_b$ baryons’ masses measured by LHCb [12]. The obtained results are summarized in Table I.

**Decay property from light-cone sum rules within HQET**

We have systematically studied various strong decay properties of $P$-wave heavy baryons in Refs. [47–49] using light-cone sum rules within HQET. There are indeed a lot of decay processes that can happen. However, in the present case the only possible strong decay mode for $P$-wave $\Omega_b$ baryons is decaying into $\Xi_b K$ (given their largest mass to be the mass of the $\Omega_b(6350)^-$, so that all the other strong decay modes are kinematically forbidden).

Actually, we can draw even stronger conclusions:

- All the $S$-wave decays of $P$-wave $\Omega_b$ baryons into ground-state heavy baryons and light pseudoscalar mesons can not happen, except

$$\Gamma \left( \Omega_b(1/2^-), 0, 1, \lambda \right) \to \Xi_b K = 2800^{+3600}_{-1800} \text{ MeV}. \quad (6)$$

The above value is evaluated through

$$\mathcal{L} = g \bar{\Omega}_b(1/2^-) \Xi_b K, \quad (7)$$

using the mass of $[\Omega_b(1/2^-), 0, 1, \lambda]$ given in Table I.

- All the decays of $P$-wave $\Omega_b$ baryons into ground-state heavy baryons and light vector mesons (as intermediate states) can not happen.

Recently, we have systematically studied $D$-wave decays of $P$-wave heavy baryons into ground-state heavy baryons and light pseudoscalar mesons [63]. The results suggest:

- All the $D$-wave decays of $P$-wave $\Omega_b$ baryons into ground-state heavy baryons and light pseudoscalar mesons can not happen, except

$$\Gamma \left( \Omega_b(3/2^-), 2, 1, \lambda \right) \to \Xi_b K = 4.7^{+6.1}_{-2.9} \text{ MeV}, \quad (8)$$

and b) $[\Omega_b(1/2^-), 0, 1, \lambda \to \Xi_b K$. The former one is evaluated through

$$\mathcal{L}' = g' \bar{\Omega}_b(3/2^-) \gamma^\nu \gamma_5 \Xi_b \partial_\mu \partial_\nu K, \quad (9)$$
TABLE I: Mass spectra of P-wave $\Omega_b$ baryons belonging to the bottom baryon multiplets $[6_F, 1, 0, \rho]$, $[6_F, 0, 1, \lambda]$, $[6_F, 1, 1, \lambda]$, and $[6_F, 2, 1, \lambda]$. There is considerable theoretical uncertainty in our results for absolute values of the masses due to their (almost) dependence on the bottom quark mass, but the mass differences within the same doublet do not depend much on the bottom quark mass, so they are produced quite well with much less theoretical uncertainty.

| Multiplets                        | $\omega_c$  | Working region $T$ | $\Lambda$  | Baryon $(j^P)$ | Mass (GeV) | Difference (MeV) | $f$ (GeV) |
|----------------------------------|-------------|--------------------|-------------|---------------|-------------|------------------|---------|
| $[6_F(\Omega_b), 1, 0, \rho]$   | 2.13        | $0.26 < T < 0.37$  | 1.58$^{+0.10}_{-0.08}$ | $\Omega_b(1/2^-)$ | 6.32$^{+0.12}_{-0.10}$ | 2.3$^{+1.0}_{-0.9}$ | 0.13$^{+0.03}_{-0.02}$ |
| $[6_F(\Omega_b), 0, 1, \lambda]$ | 2.00        | $0.27 < T < 0.34$  | 1.54$^{+0.08}$ | $\Omega_b(1/2^-)$ | 6.34$^{+0.11}$ | -                | 0.13$^{+0.02}_{-0.01}$ |
| $[6_F(\Omega_b), 1, 1, \lambda]$ | 2.00        | $0.38 < T < 0.39$  | 1.49$^{+0.07}$ | $\Omega_b(1/2^-)$ | 6.34$^{+0.09}_{-0.08}$ | 6.3$^{+2.3}_{-2.1}$ | 0.12$^{+0.02}_{-0.01}$ |
| $[6_F(\Omega_b), 2, 1, \lambda]$ | 2.08        | $0.26 < T < 0.37$  | 1.53$^{+0.11}_{-0.08}$ | $\Omega_b(3/2^-)$ | 6.35$^{+0.13}_{-0.11}$ | 10.0$^{+4.6}_{-3.8}$ | 0.16$^{+0.04}_{-0.03}$ |

TABLE II: Strong decay properties of P-wave $\Omega_b$ baryons belonging to the bottom baryon multiplets $[6_F, 1, 0, \rho]$, $[6_F, 0, 1, \lambda]$, $[6_F, 1, 1, \lambda]$, and $[6_F, 2, 1, \lambda]$. In the third and fourth columns we show the results for the S- and D-wave decays of P-wave $\Omega_b$ baryons into $\Xi_b K$ (both $\Xi_b^0 K^-$ and $\Xi_b^\pm K^0$), respectively. A.M.F. means that these channels are forbidden due to the conservation of angular momentum; K.F. means that these channels are kinematically forbidden; 0 means that decay widths of these channels are calculated to be zero; · · · means that this channel is not calculated.

| Multiplets                        | Baryon $(j^P)$ | S-wave $\Xi_b K$ | D-wave $\Xi_b K$ | $\Xi_b^0 K/\Xi_b^\pm K/\Xi_b K$ · · · |
|----------------------------------|---------------|------------------|------------------|--------------------------------------|
| $[6_F(\Omega_b), 1, 0, \rho]$   | $\Omega_b(1/2^-)$ | 0                | 0                | K.F.                                 |
|                                  | $\Omega_b(3/2^-)$ | A.M.F.           | 0                | K.F.                                 |
| $[6_F(\Omega_b), 0, 1, \lambda]$ | $\Omega_b(1/2^-)$ | $\Gamma = 2800^{+3009}_{-1808}$ MeV | -                | K.F.                                 |
| $[6_F(\Omega_b), 1, 1, \lambda]$ | $\Omega_b(1/2^-)$ | 0                | 0                | K.F.                                 |
|                                  | $\Omega_b(3/2^-)$ | A.M.F.           | 0                | K.F.                                 |
| $[6_F(\Omega_b), 2, 1, \lambda]$ | $\Omega_b(3/2^-)$ | A.M.F.           | $\Gamma = 4.7^{+6.1}_{-2.9}$ MeV | K.F.                                 |
|                                  | $\Omega_b(5/2^-)$ | A.M.F.           | 0                | K.F.                                 |

using the mass of the $\Omega_b(6350)^-$ measured by LHCB [12]. The latter is not calculated because the width of its corresponding S-wave decay mode is already too large.

We summarize the above decay properties in Table II.

**Excited $\Omega_b$ baryons in the heavy quark effective theory** — Based on Tables I and II, we can well understand the four excited $\Omega_b$ baryons observed by LHCB [12] as P-wave $\Omega_b$ baryons. There are altogether seven P-wave $\Omega_b$ baryons, belonging to four multiplets:

$\Omega_b(1/2^-), \Omega_b(3/2^-) \in [6_F, 1, 0, \rho]$,
$\Omega_b(1/2^-) \in [6_F, 0, 1, \lambda]$,
$\Omega_b(1/2^-), \Omega_b(3/2^-) \in [6_F, 1, 1, \lambda]$,
$\Omega_b(3/2^-), \Omega_b(5/2^-) \in [6_F, 2, 1, \lambda]$.

Our results suggest:

- The width of $[\Omega_b(1/2^-), 0, 1, \lambda]$ is too large for it to be observed in experiments.
- Only the natural width of the $\Omega_b(6350)^-$ was measured by LHCB to be “2.5σ from zero”, that is $\Gamma_{\Omega_b(6350)^-} = 1.4^{+1.0}_{-0.8} \pm 0.1$ MeV [12]. Its best candidate is $[\Omega_b(3/2^-), 2, 1, \lambda]$, whose width is calculated to be $\Gamma_{[\Omega_b(3/2^-), 2, 1, \lambda]} = 4.7^{+6.1}_{-2.9}$ MeV, quite narrow because this is a D-wave decay mode. The $\Omega_b(6350)^-$ is the partner state of the $\Sigma_b(6097)^\pm$ [11] and $\Xi_b(6227)^-$ [10], and it has another partner state, $[\Omega_b(5/2^-), 2, 1, \lambda]$, whose mass is $10.0^{+4.6}_{-3.8}$ MeV larger.
- The natural widths of the $\Omega_b(6330)^-$ and $\Omega_b(6340)^-$ were both measured by LHCB to be “consistent with zero”, and their mass difference was measured to be about 9.4 MeV [12]. Their best candidates are $[\Omega_b(1/2^-), 1, 1, \lambda]$ and
structure of the four excited $\Omega_b$ baryons observed by LHCb [12] is directly related to the rich internal structure of $P$-wave $\Omega_b$ baryons. Recalling that the development of quantum theory is sometimes closely related to the better understanding of the gross, fine, and hyperfine structures of atom (hydrogen) spectra, one naturally guesses that the currently undergoing studies on heavy baryons would not only improve our understandings on their internal structures, but also enrich our knowledge of the quantum theory.

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Summary — We have systematically studied mass spectra and strong decay properties of $P$-wave $\Omega_b$ baryons using the methods of QCD sum rules and light-cone sum rules within the framework of heavy quark effective theory. Although there is considerable theoretical uncertainty in our results for absolute values of the masses due to their (almost linear) dependence on the bottom quark mass, the mass differences within the same doublet due to their (almost linear) dependence on the bottom quark mass have natural widths “consistent with zero” but they can still be observed in the $\Xi_bK$ mass spectrum [12]: the HQET is an effective theory, so the three $J = 1/2^-$ $\Omega_b$ states can mix together and the three $J = 3/2^-$ ones can also mix together, making it possible to observe them in the $\Xi_bK$ mass spectrum; while the HQET works quite well for the bottom system, so this mixing is not large and some of them still have very narrow widths.

Our results suggest: the $\Omega_b(6350)^-$ is a $P$-wave $\Omega_b$ baryon with $J^P = 3/2^-$ and $\lambda$-mode excitation, and it has a $J^P = 5/2^-$ partner whose mass is $10.0^{+4.6}_{-3.8}$ MeV larger; the $\Omega_b(6330)^-$ and $\Omega_b(6340)^-$ are partner states both with $\lambda$-mode excitation, and they have $J^P = 1/2^-$ and $3/2^-$, respectively; the $\Omega_b(6316)^-$ is a $P$-wave $\Omega_b$ baryon of either $J^P = 1/2^-$ or $3/2^-$, with $\rho$-mode excitation, and it can be further separated into two states with the mass splitting $2.3^{+0.9}_{-0.9}$ MeV. The internal quantum numbers (and so internal structures) of these four excited $\Omega_b$ baryons have also been extracted, as discussed above.

To end this letter, we conclude that the beautiful fine
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