Heavy flavor baryon spectra via QCD sum rules

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In this talk, we give a short review of our recent works on studying the singly heavy baryon, doubly heavy baryon, and triply heavy baryon spectra from QCD sum rules.

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I. INTRODUCTION

The heavy baryon is an exciting and remarkable topic nowadays. Experimentally, the field of heavy hadron spectroscopy is experiencing a rapid advancement and plenty of heavy baryons have already been observed up to now \[1, 2\]. The feasibility of doubly and triply heavy baryons investigated at the Large Hadron Collider (with the design luminosity values of \(L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) and \(\sqrt{s} = 14 \text{ TeV}\)) was presented in some works, for instance, Refs. \[3, 4\]. Theoretically, various models have been utilized to compute heavy baryon masses, such as quark models \[5, 6, 7, 8, 9, 10\], mass formulas \[11, 12\], lattice QCD stimulations \[13, 14\], and other approaches \[15, 16, 17\]. One can also resort to a vigorous and reliable working tool in hadron physics, the QCD sum rules, which are still being actively used judging by the near 3500 and growing citations of the seminal papers \[18\] of M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov. The method is a nonperturbative analytic formalism firmly entrenched in QCD (for reviews see \[19, 20\] and references therein). QCD sum rules for baryons \[21\] suggested by B. L. Ioffe generalize the method from the mesonic states to the baryonic cases. With QCD sum rules, heavy baryon masses were primarily calculated by E. V. Shuryak in heavy quark limit \[22\], and subsequently in the Heavy Quark Effective Theory by some theorists, for example, A. G. Grozin, Y. B. Dai, S. Groote etc. \[23, 24, 25, 26, 27\]. There also have many works been done basing on the full theory by E. Bagan, V. V. Kiselev, T. M. Aliev, M. Nielsen etc. \[28, 29, 30, 31\], as well as our studies on singly \[32, 33\], doubly \[34\], and triply heavy baryon spectra \[35\] from QCD sum rules. Presently, we would like to briefly review our those works and make some discussions.

The content of the review is as follows. In Sec. \[III\] the main results are collected in comparison with experimental data and other approaches, followed by some discussions. Section \[IV\] contains a concise summary and outlook.

II. HEAVY BARYONS IN QCD SUM RULES

The QCD sum rule approach devotes to bridge the gap between the perturbative and nonperturbative sectors by employing the language of dispersion relations and represents an attempt to link the hadron phenomenology with the interactions of quarks and gluons. There are three leading ingredients for this method: a phenomenological description of the correlator, a theoretical description of the same correlator via an operator product expansion (OPE), and a procedure for matching these two descriptions and extracting the parameters that characterize the hadronic state of interest. Meanwhile, the QCD sum rule accuracy is limited by a very complicated hadronic dispersion integrals and by the approximations in the OPE of the correlator. The basic point of this method is the choice of appropriate interpolating current. In a tentative diquark-quark picture for the singly heavy baryon \(qqQ\) system, the \(Q\) orbits the \(qq\) pair. For the ground states, the currents are correlated with the spin-parity quantum numbers \(0^+\) and \(1^+\) for the \(qq\) diquark system, along with the heavy quark \(Q\) forming the state with \(J^P = \frac{1}{2}^+\) and the pair of
degenerate states. For the latter case, the \( qq \) diquark has spin 1, and the spin of the third quark is either parallel, \( J^P = \frac{3}{2}^+ \), or antiparallel, \( J^P = \frac{1}{2}^+ \), to the diquark. Similarly, one could assume the \( (QQ) - q \) configuration for doubly heavy baryon \( QQq \) and \( (QQ) - Q' \) for triply heavy baryon \( QQQ' \), respectively. Thereby, we principally adopt the similar forms of Ioffe currents discussed minutely in Refs. [21, 22], with

\[
\begin{align*}
 j_{\lambda_Q} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime q_c, \\
 j_{\lambda_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime Q_c, \\
 j_{\lambda_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime q_{2c}, \\
 j_{\Sigma_Q} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime Q_c, \\
 j_{\Sigma_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime Q_{2c}, \\
 j_{\Sigma_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} q_{2b}) \Gamma_k^\prime q_{2c}, \\
 j_{\Xi_Q} &= \varepsilon_{abc}(q_{1a} T CT_{k} s_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} s_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{Q}^c} &= \varepsilon_{abc}(q_{1a} T CT_{k} s_b) \Gamma_k^\prime q_{2c}, \\
 j_{\Xi_Q} &= \varepsilon_{abc}(s_{1a} T CT_{k} s_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{Q}^c} &= \varepsilon_{abc}(s_{1a} T CT_{k} s_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{Q}^c} &= \varepsilon_{abc}(s_{1a} T CT_{k} s_b) \Gamma_k^\prime q_{2c},
\end{align*}
\]

for singly heavy baryons,

\[
\begin{align*}
 j_{\Xi_{QQ}} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_c, \\
 j_{\Xi_{QQ}} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_{2c}, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_{2c}, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{QQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_{2c}\]
\]

for doubly heavy baryons, and

\[
\begin{align*}
 j_{\Xi_{QQQ}} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{QQQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{QQQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_{2c}, \\
 j_{\Xi_{QQQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_c, \\
 j_{\Xi_{QQQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime Q_{2c}, \\
 j_{\Xi_{QQQ}^c} &= \varepsilon_{abc}(Q_{1a} T CT_{Q} Q_b) \Gamma_k^\prime q_{2c},
\end{align*}
\]
for triply heavy baryons. Here the index $T$ means matrix transposition, $C$ is the charge conjugation matrix, $a$, $b$, and $c$ are color indices, $Q$ and $Q'$ denote heavy quarks, and $q$ is $u$ or $d$. The choice of $\Gamma_k$ and $\Gamma'_k$ matrices are listed in TABLE I.

TABLE I: The choice of $\Gamma_k$ and $\Gamma'_k$ matrices in baryonic currents. The index $d$ in $S_d$, $L_d$, and $J_d^{\mu}$ means diquark. $[..]$ denotes the diquark in the axial vector state, and $[..]$ denotes the diquark in the scalar state.

| Baryon | quark content | $J^P$ | $S_d$ | $L_d$ | $J_d^{\mu}$ | $\Gamma_k$ | $\Gamma'_k$ |
|--------|---------------|-------|-------|-------|--------------|--------------|-------------|
| $\Lambda_Q$ | $[qq]Q$ | $\frac{1}{2}^+$ | 0 | 0 | 0 | $\gamma_5$ | 1 |
| $\Lambda'_Q$ | $[qq]Q$ | $\frac{1}{2}^-$ | 0 | 1 | $1^-$ | $\gamma_5$ | $\gamma_\mu$ |
| $\Sigma_Q$ | $\{qq\}Q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Sigma'_Q$ | $\{qq\}Q$ | $\frac{1}{2}^-$ | 0 | 0 | 0 | $\gamma_5$ | 1 |
| $\Xi_Q$ | $[qs]Q$ | $\frac{1}{2}^+$ | 0 | 1 | $1^-$ | $\gamma_\mu$ | $\gamma_\mu$ |
| $\Xi'_Q$ | $[qs]Q$ | $\frac{1}{2}^-$ | 0 | 0 | 0 | $\gamma_5$ | 1 |
| $\Omega_Q$ | $[ss]Q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Omega'_Q$ | $[ss]Q$ | $\frac{1}{2}^-$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Xi_{QQ}$ | $\{QQ\}q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Xi_{QQ'}$ | $\{QQ\}q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | 1 |
| $\Omega_{QQ}$ | $\{QQ\}s$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Omega_{QQ'}$ | $\{QQ\}s$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | 1 |
| $\Xi_{QQ'}$ | $\{QQ'\}q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Xi_{QQ''}$ | $\{QQ'\}q$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | 1 |
| $\Omega_{QQ''}$ | $\{QQ'\}s$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | $\gamma_\mu \gamma_5$ |
| $\Omega_{QQ''}$ | $\{QQ'\}s$ | $\frac{1}{2}^+$ | 1 | 0 | $1^+$ | $\gamma_\mu$ | 1 |

Concretely, coming down to the mass sum rules for the singly heavy baryon as an example, the starting point is the two-point correlator

$$\Pi(q^2) = i \int d^4 x e^{i q \cdot x} \langle 0 | T[j(x) j'(0)] | 0 \rangle. \quad (1)$$

Lorentz covariance implies that the correlator $\Pi$ has the form

$$\Pi(q^2) = \mathbb{P} \Pi_1(q^2) + \Pi_2(q^2). \quad (2)$$

For each invariant function $\Pi_1$ and $\Pi_2$, a sum rule can be obtained.

In the phenomenology side, the correlator can be expressed as a dispersion integral over a physical spectral function

$$\Pi(q^2) = \chi_H^2 \mathbb{P} + \frac{M_H}{M_H^2 - q^2} + \frac{1}{\pi} \int_{s_0}^{\infty} ds \text{Im} \Pi_{\text{phen}}(s) \frac{s}{s - q^2} + \text{subtractions}, \quad (3)$$

where $M_H$ denotes the heavy baryon mass.
In the OPE side, the correlator can be written in terms of a dispersion relation as

\[
\Pi_i(q^2) = \int_{m^2_0}^{\infty} ds \frac{\rho_i(s)}{s - q^2}, \quad i = 1, 2.
\] (4)

After equating the two sides, assuming quark-hadron duality, making a Borel transform, and eliminating the baryon coupling constant \(\lambda_H\), the sum rules can be written as,

\[
M^2_H = \int_{m^2_0}^{s_0} ds \rho_i(s) e^{-s/M^2} / \int_{m^2_0}^{s_0} ds \rho_i(s) e^{-s/M^2}, \quad i = 1, 2.
\] (5)

For brevity, more detailed descriptions of the calculation procedures will not be iterated here, which can be found in Refs. [32, 33, 34, 35]. The final results are collected together with the available experimental data and other theoretical predictions in Tables II-IV. It is worth noting that uncertainty in our results are merely due to the sum rule windows, not involving the ones rooting in the variation of the quark masses and QCD parameters. Note that the QCD \(O(\alpha_s)\) corrections are not covered in these works. However, it is expected that the QCD \(O(\alpha_s)\) corrections might be under control since a partial cancelation occurs in the ratio obtaining the mass sum rules. This has been proved to be true in the analysis for the singly heavy baryons (the radiative corrections to the perturbative terms increase the calculated baryon masses by about 10%) in Ref. [24] and for the heavy mesons (the value of \(f_D\) increases by 12% after the inclusion of the \(O(\alpha_s)\) correction) in Ref. [36]. Although the mass values for doubly heavy baryons are consistent with other theoretical predictions, some of the absolute differences from them are not small, for instance, the masses of \(\Xi_{cc}\), \(\Omega_{cc}\), and \(\Xi^*_{cb}\), whereas, the relative discrepancies are in the tolerable ranges of the sum rule accuracy. Visually, the Borel curves for \(\Xi_{cc}\), \(\Omega_{cc}\), and \(\Xi^*_{cb}\) are not very flat, but it is difficult to find much better sum rule windows. That’s probably because the condensate contributions for them, which may play an important role in stabilizing the Borel curves, nearly vanished or are small. The stability of those three curves might be improved by including some higher dimension condensate contributions. For triply heavy baryons, one can find that our central values are lower than potential model predictions, in particular, for \(\Omega_{bb}\), slightly more than 1 GeV, whereas the relative discrepancy approximates to 10%, which is still acceptable. In addition, our result for \(\Omega_{ccc}\) agrees well with the lattice QCD value in Ref. [14], but the other comparisons for triply heavy baryons cannot be made for the absence of relevant lattice results by this time.

### III. SUMMARY AND OUTLOOK

In summary, we have studied the mass spectra of singly, doubly, and triply heavy baryons in the framework of full QCD sum rules and arrived at three conclusions in chief. First, our results for singly heavy baryons are well compatible with the existing experimental data. Second, the mass values for doubly heavy baryons are in reasonable accord with other predictions. Third, the numerical results for triply heavy baryons are lower than the predictions from potential models, nevertheless, the one for \(\Omega_{ccc}\) is in good agreement with the lattice study.

Though enormous progress have been achieved in experimental and theoretical aspects for the heavy flavor baryons, there are still many problems desiderated to resolve. In experiment, it is worthy to point out that most of the \(J^P\) quantum numbers for the observed heavy baryons have not been determined, but are assigned by PDG on the basis of quark model predictions, which are looking forward to further experimental identification, particularly for some higher excited states. More data on singly bottom baryons and doubly heavy baryons, along with the evidence on triply heavy baryons are earnestly expected after the Large Hadron Collider startup, which may supply a gap of experimental data in the future. Theoretically, in order to improve on the accuracy of the QCD sum rule analysis for the heavy baryons, especially for triply heavy baryons, one needs to take into account the QCD \(O(\alpha_s)\) corrections to the sum rules in the further
TABLE III: The mass spectra of doubly heavy baryons (mass in unit of GeV).

| Baryon content | \( J^{P} \) | \( S_d \) | \( L_d \) | \( J^{P'} \) | Our work [34] | Ref. [6] | Ref. [12] | Ref. [15] | Refs. [28] | Refs. [29] |
|----------------|-----------|----------|----------|-----------|----------------|------|------|------|---------|---------|
| \( \Xi_{cc} \)   | \[cc\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 4.26 ± 0.19 | 3.620 | 3.676 | 3.520 | 3.55 ± 0.08 | 3.48 ± 0.06 |
| \( \Xi_{cc} \)   | \[cc\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 3.90 ± 0.10 | 3.727 | 3.746 | 3.63  | 3.58 ± 0.05 |
| \( \Omega_{cc} \) | \[cc\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 4.25 ± 0.20 | 3.778 | 3.787 | 3.619 | 3.65 ± 0.07 |
| \( \Omega_{cc} \) | \[cc\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 3.81 ± 0.06 | 3.872 | 3.851 | 3.721 |            |
| \( \Xi_{bb} \)   | \[bb\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 9.78 ± 0.07 | 10.202 | 10.272 | 10.00 ± 0.08 | 9.94 ± 0.91 |
| \( \Xi_{bb} \)   | \[bb\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 10.35 ± 0.08 | 10.237 | 10.398 | 10.337 | 10.33 ± 1.09 |
| \( \Omega_{bb} \) | \[bb\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 9.85 ± 0.07 | 10.359 | 10.369 | 10.09 ± 0.07 |
| \( \Omega_{bb} \) | \[bb\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 10.28 ± 0.05 | 10.389 | 10.483 | 10.429 |            |
| \( \Xi_{bb} \)   | \[cb\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 6.75 ± 0.05 | 6.933 | 7.053 | 6.838 | 6.79 ± 0.08 |
| \( \Xi_{bb} \)   | \[cb\]q   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 8.00 ± 0.26 | 6.980 | 7.083 | 6.986 |            |
| \( \Omega_{bb} \) | \[cb\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 7.02 ± 0.08 | 7.088 | 7.148 | 6.941 | 6.89 ± 0.07 |
| \( \Omega_{bb} \) | \[cb\]s   | \( \frac{1}{2}^+ \) | 1   | 0  | 1^+                   | 7.54 ± 0.08 | 7.130 | 7.165 | 7.077 |            |
| \( \Xi_{bb} \)   | \[cb\]q   | \( \frac{1}{2}^+ \) | 0   | 0  | 0^+                   | 6.95 ± 0.08 | 6.963 | 7.062 | 7.028 | 6.44 ± 0.19 |
| \( \Omega_{bb} \) | \[cb\]s   | \( \frac{1}{2}^+ \) | 0   | 0  | 0^+                   | 7.02 ± 0.08 | 7.116 | 7.151 | 7.116 |            |
work. Additionally, it is interesting to carry out a comprehensive study on triply heavy baryon spectra from lattice QCD for the future.

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| Baryon quark content | \( J^P \) | \( S_d \) | \( L_d \) | \( J^P_d \) | Our work | Ref. [8] | Ref. [9] | Ref. [10] | Ref. [14] | Ref. [16] |
|----------------------|--------|--------|--------|--------|----------|--------|--------|--------|--------|--------|
| \( \Omega_{ccc} \)   | \{cc\}c | \( \frac{1}{2}^+ \) | 1 | 0 | 1^+ | 4.67 ± 0.15 | 4.803 | 4.79 | 4.925 | 4.681 | 4.76 |
| \( \Omega_{bbb} \)   | \{bb\}b | \( \frac{3}{2}^+ \) | 1 | 0 | 1^+ | 13.28 ± 0.10 | 14.569 | 14.30 | 14.760 | 14.37 |
| \( \Omega_{ccb} \)   | \{cc\}b | \( \frac{1}{2}^+ \) | 1 | 0 | 1^+ | 7.41 ± 0.13 | 8.018 |
| \( \Omega_{*ccb} \)  | \{cc\}b | \( \frac{3}{2}^+ \) | 1 | 0 | 1^+ | 7.45 ± 0.16 | 8.025 | 8.03 | 8.200 | 7.98 |
| \( \Omega_{mbc} \)   | \{bb\}c | \( \frac{1}{2}^+ \) | 1 | 0 | 1^+ | 10.30 ± 0.10 | 11.280 |
| \( \Omega_{*mbc} \)  | \{cb\}c | \( \frac{3}{2}^+ \) | 1 | 0 | 1^+ | 10.54 ± 0.11 | 11.287 | 11.20 | 11.480 | 11.19 |
| \( \Omega_{*mbc} \)  | \{cc\}b | \( \frac{1}{2}^+ \) | 0 | 0 | 0^+ | 7.49 ± 0.10 |
| \( \Omega_{mbc} \)   | \{bb\}c | \( \frac{1}{2}^+ \) | 0 | 0 | 0^+ | 10.35 ± 0.07 |

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