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Heavy flavor baryon spectra via QCD sum rules*

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Abstract 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.

Key words singly heavy baryon, doubly heavy baryon, triply heavy baryon, QCD sum rules

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1 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 $\mathcal{L}=10^{34}$ cm^{-2}s^{-1} and $\sqrt{s}=14$ 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—10], mass formulas[11, 12], lattice QCD simulations[13, 14], and other approaches[15—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—27]. There are also many works been done basing on the full theory by E. Bagan, V. V. Kiselev, T. M. Aliev, M. Nielsen etc.[28—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 those works and make some discussions.

2 Heavy baryons in QCD sum rules

The QCD sum rule approach represents an attempt to link the hadron phenomenology with the interactions of quarks and gluons. 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 $(\mathrm{QQ})-\mathrm{q}$ configuration for doubly heavy baryon QQq and $(\mathrm{QQ})-\mathrm{Q}'$ for triply heavy baryon QQQ$'$, respectively. Thereby, we principally adopt the similar forms of Ioffe currents discussed minutely in Refs. [21, 22].

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

$$\Pi(q^2)=\mathrm{i}\int \mathrm{d}^4x\mathrm{e}^{\mathrm{i}q\cdot x}\langle 0|T[j(x)\overline{j}(0)]|0\rangle. \qquad (1)$$

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Lorentz covariance implies that the correlator (1) has the form

$$\Pi(q^2)=\not{q}\,\Pi_1(q^2)+\Pi_2(q^2). \tag{2}$$

For each invariant function Π_1 and Π_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

$$\Pi(q^2)=\lambda_H^2\frac{\not{q}+M_H}{M_H^2-q^2}+\frac{1}{\pi}\int_{s_0}^{\infty}\mathrm{d}s\frac{\mathrm{Im}\Pi^{\mathrm{phen}}(s)}{s-q^2}+\text{subtractions}, \tag{3}$$

where M_H denotes the heavy baryon mass.

In the OPE side, the correlator can be written in terms of a dispersion relation as

$$\Pi_i(q^2)=\int_{m_Q^2}^{\infty}\mathrm{d}s\frac{\rho_i(s)}{s-q^2},\quad i=1,2. \tag{4}$$

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

$$M_H^2=\int_{m_Q^2}^{s_0}\mathrm{d}s\rho_i(s)s\mathrm{e}^{-s/M^2}\Big/\int_{m_Q^2}^{s_0}\mathrm{d}s\rho_i(s)\mathrm{e}^{-s/M^2},\quad i=1,2. \tag{5}$$

For brevity, more detailed descriptions of the calculation procedures will not be iterated here. The final results are collected together with the available experimental data and other theoretical predictions in Tables 1—3. 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 $\mathrm{O}(\alpha_{\mathrm{s}})$ corrections are not covered in these works. However, it is expected that the QCD $\mathrm{O}(\alpha_{\mathrm{s}})$ 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 in Ref. [24] and for the heavy mesons 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 Ξ_{cc}, Ω_{cc}, and Ξ_{cb}^*, whereas, the relative discrepancies are in the tolerable ranges of the sum rule accuracy. Visually, the Borel curves for Ξ_{cc}, Ω_{cc}, and Ξ_{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

Table 1. The mass spectra of charmed and bottom baryons (mass in unit of MeV except for "Our works").

baryon	J^P	S_ℓ	L_ℓ	$J_\ell^{P_\ell}$	experiments[1, 2]	our works (GeV)[32, 33]	Ref. [5]	Ref. [11]	Ref. [13]	Ref. [26]
Λ_{c}^+	$\frac{1}{2}^+$	0	0	0^+	2286.46 ± 0.14	2.31 ± 0.19	2297	2285	2290	2271^{+67}_{-49}
$\Lambda_{\mathrm{c}}(2593)^+$	$\frac{1}{2}^-$	0	1	1^-	2595.4 ± 0.6	2.53 ± 0.22	2598			
$\Lambda_{\mathrm{c}}(2625)^+$	$\frac{3}{2}^-$	0	1	1^-	2628.1 ± 0.6	2.58 ± 0.24	2628			
$\Sigma_{\mathrm{c}}(2455)^0$	$\frac{1}{2}^+$	1	0	1^+	2453.76 ± 0.18	2.40 ± 0.31	2439	2453	2452	2411^{+93}_{-81}
$\Sigma_{\mathrm{c}}(2520)^0$	$\frac{3}{2}^+$	1	0	1^+	2518.0 ± 0.5	2.56 ± 0.24	2518	2520	2538	2534^{+96}_{-81}
Ξ_{c}^0	$\frac{1}{2}^+$	0	0	0^+	2471.0 ± 0.4	2.48 ± 0.21	2481	2468	2473	2432^{+79}_{-68}
$\Xi_{\mathrm{c}}(2790)^0$	$\frac{1}{2}^-$	0	1	1^-	2791.9 ± 3.3	2.65 ± 0.27	2801			
$\Xi_{\mathrm{c}}(2815)^0$	$\frac{3}{2}^-$	0	1	1^-	2818.2 ± 2.1	2.69 ± 0.29	2820			
$\Xi_{\mathrm{c}}^{\prime 0}$	$\frac{1}{2}^+$	1	0	1^+	2578.0 ± 2.9	2.50 ± 0.29	2578	2580	2599	2508^{+97}_{-91}
$\Xi_{\mathrm{c}}(2645)^0$	$\frac{3}{2}^+$	1	0	1^+	2646.1 ± 1.2	2.64 ± 0.22	2654	2650	2680	2634^{+102}_{-94}
Ω_{c}^0	$\frac{1}{2}^+$	1	0	1^+	2697.5 ± 2.6	2.62 ± 0.29	2698	2710	2678	2657^{+102}_{-99}
$\Omega_{\mathrm{c}}(2768)^0$	$\frac{3}{2}^+$	1	0	1^+	2768.3 ± 3.0	2.74 ± 0.23	2768	2770	2752	2790^{+109}_{-105}
Λ_{b}	$\frac{1}{2}^+$	0	0	0^+	5619.7 ± 1.2	5.69 ± 0.13	5622	5620	5672	5637^{+68}_{-56}
$\Lambda_{1\mathrm{b}}$	$\frac{1}{2}^-$	0	1	1^-		5.85 ± 0.15	5930			
$\Lambda_{1\mathrm{b}}^*$	$\frac{3}{2}^-$	0	1	1^-		5.90 ± 0.16	5947			
Σ_{b}	$\frac{1}{2}^+$	1	0	1^+	$5807.8^{+2.0}_{-2.2}\pm1.7$	5.73 ± 0.21	5805	5820	5847	5809^{+82}_{-76}
Σ_{b}^*	$\frac{3}{2}^+$	1	0	1^+	$5829.0^{+1.6+1.7}_{-1.8-1.8}$	5.81 ± 0.19	5834	5850	5871	5835^{+82}_{-77}
Ξ_{b}^0	$\frac{1}{2}^+$	0	0	0^+	$5792.9\pm2.5\pm1.7$	5.75 ± 0.13	5812	5810	5788	5780^{+73}_{-68}
$\Xi_{1\mathrm{b}}$	$\frac{1}{2}^-$	0	1	1^-		5.95 ± 0.16	6119			
$\Xi_{1\mathrm{b}}^*$	$\frac{3}{2}^-$	0	1	1^-		5.99 ± 0.17	6130			
$\Xi_{\mathrm{b}}^{\prime}$	$\frac{1}{2}^+$	1	0	1^+		5.87 ± 0.20	5937	5950	5936	5903^{+81}_{-79}
$\Xi_{\mathrm{b}}^{\prime *}$	$\frac{3}{2}^+$	1	0	1^+		5.94 ± 0.17	5963	5980	5959	5929^{+83}_{-79}
Ω_{b}	$\frac{1}{2}^+$	1	0	1^+	$6165\pm10\pm13$	5.89 ± 0.18	6065	6060	6040	6036 ± 81
Ω_{b}^*	$\frac{3}{2}^+$	1	0	1^+		6.00 ± 0.16	6090	6090	6060	6063^{+83}_{-82}

Table 2. The mass spectra of doubly heavy baryons (mass in unit of GeV).

baryon	content	J^P	S_d	L_d	$J_d^{P_d}$	our work[34]	Ref. [6]	Ref. [12]	Ref. [15]	Ref. [28]	Ref. [29]
$\Xi_{\rm cc}$	{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
$\Xi^*_{\rm cc}$	{cc}q	$\frac{3}{2}^+$	1	0	1^+	3.90 ± 0.10	3.727	3.746	3.63		3.58 ± 0.05
$\Omega_{\rm cc}$	{cc}s	$\frac{1}{2}^+$	1	0	1^+	4.25 ± 0.20	3.778	3.787	3.619	3.65 ± 0.07	
$\Omega^*_{\rm cc}$	{cc}s	$\frac{3}{2}^+$	1	0	1^+	3.81 ± 0.06	3.872	3.851	3.721		
$\Xi_{\rm bb}$	{bb}q	$\frac{1}{2}^+$	1	0	1^+	9.78 ± 0.07	10.202		10.272	10.00 ± 0.08	9.94 ± 0.91
$\Xi^*_{\rm bb}$	{bb}q	$\frac{3}{2}^+$	1	0	1^+	10.35 ± 0.08	10.237	10.398	10.337		10.33 ± 1.09
$\Omega_{\rm bb}$	{bb}s	$\frac{1}{2}^+$	1	0	1^+	9.85 ± 0.07	10.359		10.369	10.09 ± 0.07	
$\Omega^*_{\rm bb}$	{bb}s	$\frac{3}{2}^+$	1	0	1^+	10.28 ± 0.05	10.389	10.483	10.429		
$\Xi_{\rm cb}$	{cb}q	$\frac{1}{2}^+$	1	0	1^+	6.75 ± 0.05	6.933	7.053	6.838	6.79 ± 0.08	
$\Xi^*_{\rm cb}$	{cb}q	$\frac{3}{2}^+$	1	0	1^+	8.00 ± 0.26	6.980	7.083	6.986		
$\Omega_{\rm cb}$	{cb}s	$\frac{1}{2}^+$	1	0	1^+	7.02 ± 0.08	7.088	7.148	6.941	6.89 ± 0.07	
$\Omega^*_{\rm cb}$	{cb}s	$\frac{3}{2}^+$	1	0	1^+	7.54 ± 0.08	7.130	7.165	7.077		
$\Xi'_{\rm cb}$	[cb]q	$\frac{1}{2}^+$	0	0	0^+	6.95 ± 0.08	6.963	7.062	7.028		6.44 ± 0.19
$\Omega'_{\rm cb}$	[cb]s	$\frac{1}{2}^+$	0	0	0^+	7.02 ± 0.08	7.116	7.151	7.116		

Table 3. The mass spectra of triply heavy baryons (mass in unit of GeV).

baryon	quark content	J^P	S_d	L_d	$J_d^{P_d}$	our work[35]	Ref. [8]	Ref. [9]	Ref. [10]	Ref. [14]	Ref. [16]
$\Omega_{\rm ccc}$	{cc}c	$\frac{3}{2}^+$	1	0	1^+	4.67 ± 0.15	4.803	4.79	4.925	4.681	4.76
$\Omega_{\rm bbb}$	{bb}b	$\frac{3}{2}^+$	1	0	1^+	13.28 ± 0.10	14.569	14.30	14.760		14.37
$\Omega_{\rm ccb}$	{cc}b	$\frac{1}{2}^+$	1	0	1^+	7.41 ± 0.13	8.018				
$\Omega^*_{\rm ccb}$	{cc}b	$\frac{3}{2}^+$	1	0	1^+	7.45 ± 0.16	8.025	8.03	8.200		7.98
$\Omega_{\rm bbc}$	{bb}c	$\frac{1}{2}^+$	1	0	1^+	10.30 ± 0.10	11.280				
$\Omega^*_{\rm bbc}$	{bb}c	$\frac{3}{2}^+$	1	0	1^+	10.54 ± 0.11	11.287	11.20	11.480		11.19
$\Omega'_{\rm ccb}$	[cc]b	$\frac{1}{2}^+$	0	0	0^+	7.49 ± 0.10					
$\Omega'_{\rm bbc}$	[bb]c	$\frac{1}{2}^+$	0	0	0^+	10.35 ± 0.07					

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 $\Omega_{\rm bbb}$, slightly more than 1 GeV, whereas the relative discrepancy approximates to 10%, which is still acceptable. In addition, our result for $\Omega_{\rm ccc}$ 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.

3 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 $\Omega_{\rm ccc}$ is in good agreement with the lattice study.

Anyhow, 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 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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