

Masses and residues of the triply heavy spin-1/2 baryons

T. M. Aliev,^a K. Azizi^b and M. Savcı^a

^a*Department of Physics, Middle East Technical University,
06531 Ankara, Turkey*

^b*Department of Physics, Doğuş University,
Acıbadem-Kadıköy, 34722 İstanbul, Turkey*

E-mail: taliev@metu.edu.tr, *e-mail:* kazizi@dogus.edu.tr,
savci@metu.edu.tr

ABSTRACT: We calculate the masses and residues of the triply heavy spin-1/2 baryons using the most general form of their interpolating currents within the QCD sum rules method. We compare the obtained results with the existing theoretical predictions in the literature.

KEYWORDS: QCD Phenomenology, Phenomenological Models

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1 Introduction

Recently, there have been significant experimental success on the identification and spectroscopy of the baryons containing heavy bottom and charm quarks. By this time, all baryons containing a single charm quark have been detected as predicted by the quark model. The heavy Λ_b , Σ_b , Ξ_b and Ω_b baryons with spin-1/2 and spin-3/2 Σ_b^* baryon containing a single bottom quark have also been discovered (for the current status of the heavy flavor baryons see, for example, the review [1]). Recently, CMS Collaboration at CERN reported the observation of the spin-3/2 heavy Ξ_b^* baryon [2]. SELEX Collaboration announced the first observation of the doubly heavy spin-1/2 Ξ_{cc}^+ baryon with two charm quarks [3–5]. We hope that the LHCb detector at CERN will provide us with identification and detection of all doubly heavy and triply heavy baryons predicted by the quark model.

The experimental progresses on the spectroscopy of the heavy baryons have stimulated the theoretical studies in this respect. In literature there are many works on the spectroscopy of the heavy baryons with a single heavy quark. There are also dozens of works dedicated to the spectroscopy of the doubly heavy baryons. However, the number of works devoted to the investigation of the properties of the triply heavy baryons are quite limited. The spectroscopy of the triply heavy baryons are discussed within different approaches such as the effective field theory, lattice QCD, QCD bag model, various quark models, variational approach, hyper central model, potential model and Regge trajectory ansatz in [6–18]. The masses and residues of the triply heavy baryons for the Ioffe current within QCD sum rules method are calculated in [19, 20].

In the present work we extend our previous studies on the spectroscopy and mixing angles of the doubly heavy baryons [21–23] to the triply heavy baryons. We calculate the masses and residues of the triply heavy spin-1/2 baryons using the most general form of their interpolating currents within the QCD sum rules method. We compare our results with the QCD sum rule predictions obtained using, the so called, Ioffe current [19, 20], as well as with the predictions of other theoretical approaches [6–18].

The layout of the article is as follows. In section 2, we derive QCD sum rules for the masses and residues of the triply heavy spin-1/2 baryons. In section 3, we numerically

Baryon	Q	Q'
Ω_{bbc}	b	c
Ω_{ccb}	c	b

Table 1. The quark contents of the triply heavy spin-1/2 baryons.

analyze the sum rules for the masses and residues and find the reliable working regions for the auxiliary parameters that enter to the sum rules. We compare and discuss our numerical results with the predictions of the theoretical works existing in the literature.

2 Masses and residues of the triply heavy spin-1/2 baryons

In order to obtain the QCD sum rules for the masses and residues of the triply heavy baryons we start our analysis by considering the correlation function

$$\Pi(q) = i \int d^4x e^{iqx} \langle 0 | \mathcal{T} \{ \eta_{QQQ'}(x) \bar{\eta}_{QQQ'}(0) \} | 0 \rangle, \quad (2.1)$$

where $\eta_{QQQ'}$ is the interpolating current for the baryons under investigation and q is their four-momentum. The most general form of the interpolating current for the triply heavy spin-1/2 baryons can be written as

$$\eta_{QQQ'} = 2\epsilon_{ijk} \left\{ \left(Q^{iT} C Q'^j \right) \gamma_5 Q^k + \beta \left(Q^{iT} C \gamma_5 Q'^j \right) Q^k \right\}, \quad (2.2)$$

where i, j, k are the color indices, C is the charge conjugation operator and β is an arbitrary auxiliary parameter whose working region is to be determined. The case $\beta = -1$ in eq. (2.2) corresponding to the Ioffe current is considered in [19, 20]. The heavy Q and Q' quarks contents of the triply heavy baryons predicted by the quark model is given in table 1. From the current given in eq. (2.2) one can formally obtain the interpolating current of the proton (neutron) by replacing $Q \rightarrow u$ and $Q' \rightarrow d$ ($Q \rightarrow d$ and $Q' \rightarrow u$).

The correlation function in eq. (2.1) can be calculated in two different ways. On the physical (or phenomenological) side it is calculated in terms of the hadronic states, while on the QCD side it is evaluated in terms of quarks and gluons. Matching these two representations then gives us the QCD sum rules for physical quantities under consideration. To suppress the contributions of the higher states and continuum we apply Borel transformation, as well as continuum subtraction to both sides of the obtained sum rules.

By saturating the correlation function on the physical side with a complete set of hadronic states having the same quantum numbers as the interpolating current and isolating the ground state baryons, we get

$$\Pi(q) = \frac{\langle 0 | \eta_{QQQ'}(0) | B(q) \rangle \langle B(q) | \bar{\eta}_{QQQ'}(0) | 0 \rangle}{q^2 - m_B^2} + \dots, \quad (2.3)$$

where dots stand for the contributions coming from the higher states and continuum. The matrix element of the interpolating current between the vacuum and the baryonic state is parameterized as,

$$\langle 0 | \eta_{QQQ'}(0) | B(q, s) \rangle = \lambda_{Bu}(q, s), \quad (2.4)$$

where λ_B is the residue of the heavy spin-1/2 baryons and $u(q, s)$ is their Dirac spinor. By performing summation over the spins of these baryons, we obtain

$$\Pi(q) = \frac{\lambda_B^2(\not{q} + m_B)}{q^2 - m_B^2} + \dots, \quad (2.5)$$

for the physical side, in which only two independent Lorentz structures \not{q} and the identity matrix I survive to be able to calculate the masses and residues of the relevant baryons.

On the QCD side, the correlation function is calculated using the operator product expansion (OPE) in deep Euclidean region. By applying the Wick theorem and contracting out all quark fields, we obtain the following expression in terms of the heavy quark propagators:

$$\begin{aligned} \Pi(q) = & 4i\epsilon_{ijk}\epsilon_{lmn} \int d^4x e^{iqx} \langle 0 | \left\{ -\gamma_5 S_Q^{nj} S_{Q'}^{mi} S_Q^{lk} \gamma_5 + \gamma_5 S_Q^{nk} \gamma_5 \text{Tr} \left[S_Q^{lj} S_{Q'}^{mi} \right] \right. \\ & + \beta \left(-\gamma_5 S_Q^{nj} \gamma_5 S_{Q'}^{mi} S_Q^{lk} - S_Q^{nj} S_{Q'}^{mi} \gamma_5 S_Q^{lk} \gamma_5 + \gamma_5 S_Q^{nk} \text{Tr} \left[S_Q^{lj} \gamma_5 S_{Q'}^{mi} \right] \right. \\ & \left. \left. + S_Q^{nk} \gamma_5 \text{Tr} \left[S_Q^{lj} S_{Q'}^{mi} \gamma_5 \right] \right) + \beta^2 \left(-S_Q^{nj} \gamma_5 S_{Q'}^{mi} \gamma_5 S_Q^{lk} + S_Q^{nk} \text{Tr} \left[S_{Q'}^{mi} \gamma_5 S_Q^{lj} \gamma_5 \right] \right) \right\} | 0 \rangle, \end{aligned} \quad (2.6)$$

where $S' = CS^T C$.

To proceed on the QCD side, we write the coefficients of the selected structures in terms of the dispersion integral as follows,

$$\Pi_i(q) = \int \frac{\rho_i(s)}{s - q^2} ds, \quad (2.7)$$

where $\rho_i(s)$ are the spectral densities and they are determined from the imaginary parts of the $\Pi_i(q)$ functions. Here $i = 1$ and 2 correspond to the structures \not{q} and I , respectively. Our main task in the following is the calculation of these spectral densities. Furthermore, we need the explicit expression of the heavy quark propagator which is given as,

$$\begin{aligned} S_Q(x) = & \frac{m_Q^2}{4\pi^2} \frac{K_1(m_Q \sqrt{-x^2})}{\sqrt{-x^2}} - i \frac{m_Q^2 \not{x}}{4\pi^2 x^2} K_2(m_Q \sqrt{-x^2}) \\ & - ig_s \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \int_0^1 du \left[\frac{\not{k} + m_Q}{2(m_Q^2 - k^2)^2} G^{\mu\nu}(ux) \sigma_{\mu\nu} + \frac{u}{m_Q^2 - k^2} x_\mu G^{\mu\nu} \gamma_\nu \right] + \dots, \end{aligned} \quad (2.8)$$

where K_1 and K_2 are the modified Bessel functions of the second kind. Substituting this expression of the heavy quark propagator in eq. (2.6) and after performing lengthy

calculations we obtain the spectral densities

$$\begin{aligned}
 \rho_1(s) = & \frac{1}{64\pi^4} \int_{\psi_{\min}}^{\psi_{\max}} \int_{\eta_{\min}}^{\eta_{\max}} d\psi d\eta \left\{ -3\mu_{QQQ'} \left[-12(-1+\eta)m_Q m_{Q'}(-1+\beta)^2 \right. \right. \\
 & + \psi^2 \eta (3\mu_{QQQ'} - 2s) [5 + \beta(2+5\beta)] + \psi \left(2m_Q^2(-1+\beta)^2 - 12m_Q m_{Q'}(-1+\beta^2) \right. \\
 & \left. \left. + (-1+\eta)\eta(3\mu_{QQQ'} - 2s) [5 + \beta(2+5\beta)] \right) \right] \left. \right\} \\
 & + \frac{\langle g_s^2 GG \rangle}{256\pi^4 m_Q m_{Q'}} \int_{\psi_{\min}}^{\psi_{\max}} \int_{\eta_{\min}}^{\eta_{\max}} d\psi d\eta \left\{ 6(-3+4\psi)(-1+\psi+\eta)m_Q^2(-1+\beta^2) \right. \\
 & + 6(-3+4\eta)(-1+\psi+\eta)m_{Q'}^2(-1+\beta^2) + m_Q m_{Q'} \left[48\psi^2(1+\beta^2) + \psi \left[-63 \right. \right. \\
 & + 68\eta - 30\beta + 8\eta\beta + (-63+68\eta)\beta^2 \right] + 2(-1+\eta) \left(-3[3+\beta(2+3\beta)] \right. \\
 & \left. \left. + 2\eta[5+\beta(2+5\beta)] \right) \right] \left. \right\}, \tag{2.9}
 \end{aligned}$$

$$\begin{aligned}
 \rho_2(s) = & \frac{1}{32\pi^4} \int_{\psi_{\min}}^{\psi_{\max}} \int_{\eta_{\min}}^{\eta_{\max}} d\psi d\eta \left\{ 3\mu_{QQQ'} \left[\eta(-1+\psi+\eta)m_{Q'}(\mu_{QQQ'} - s)(-1+\beta)^2 \right. \right. \\
 & \left. \left. + 6\psi(-1+\psi+\eta)m_Q(\mu_{QQQ'} - s)(-1+\beta^2) + m_Q^2 m_{Q'} [5 + \beta(2+5\beta)] \right] \right\} \\
 & + \frac{\langle g_s^2 GG \rangle}{128\pi^4 m_Q m_{Q'}} \int_{\psi_{\min}}^{\psi_{\max}} \int_{\eta_{\min}}^{\eta_{\max}} \frac{d\psi d\eta}{\psi\eta} \left\{ -2(-1+\eta)\eta m_Q m_{Q'}^2(-1+\beta)^2 \right. \\
 & - 2\psi^3 \eta(-1+\beta) \left[-9m_{Q'}(\mu_{QQQ'} - s)(1+\beta) + \eta(2\mu_{QQQ'} - 3s)(m_Q(-1+\beta) \right. \\
 & \left. + 6m_{Q'}(1+\beta)) \right] + \psi m_Q \left(3\eta^3(\mu_{QQQ'} - s)(-1+\beta)^2 + 2m_Q m_{Q'}(-1+\beta^2) \right. \\
 & \left. + 3\eta^2 \left[-[(\mu_{QQQ'} - s)(-1+\beta)^2] + 2m_Q m_{Q'}(-1+\beta^2) + 4m_{Q'}^2(1+\beta^2) \right] \right. \\
 & \left. + \eta \left[-5m_{Q'}^2(-1+\beta)^2 - 2m_Q m_{Q'}(-1+\beta^2) + m_Q^2 [5 + \beta(2+5\beta)] \right] \right) \\
 & + \psi^2 \left(-4m_Q^2 m_{Q'}(-1+\beta^2) + \eta^2(7\mu_{QQQ'} - 9s)(-1+\beta) [m_Q(-1+\beta) + 6m_{Q'}(1+\beta)] \right. \\
 & \left. - 2\eta^3(2\mu_{QQQ'} - 3s)(-1+\beta) [m_Q(-1+\beta) + 6m_{Q'}(1+\beta)] + \eta \left[-18m_{Q'}(\mu_{QQQ'} - s) \right. \right. \\
 & \left. \left. \times (-1+\beta^2) + 12m_Q m_{Q'}^2(1+\beta^2) - m_Q^3 [5 + \beta(2+5\beta)] \right] \right) \left. \right\}, \tag{2.10}
 \end{aligned}$$

where,

$$\begin{aligned}
 \mu_{QQQ'} &= \frac{m_Q^2}{1-\psi-\eta} + \frac{m_Q^2}{\eta} + \frac{m_{Q'}^2}{\psi} - s, \\
 \eta_{\min} &= \frac{1}{2} \left[1 - \psi - \sqrt{(1-\psi) \left(1 - \psi - \frac{4\psi m_Q^2}{\psi s - m_{Q'}^2} \right)} \right], \\
 \eta_{\max} &= \frac{1}{2} \left[1 - \psi + \sqrt{(1-\psi) \left(1 - \psi - \frac{4\psi m_Q^2}{\psi s - m_{Q'}^2} \right)} \right], \\
 \psi_{\min} &= \frac{1}{2s} \left[s + m_{Q'}^2 - 4m_Q^2 - \sqrt{(s + m_{Q'}^2 - 4m_Q^2)^2 - 4m_{Q'}^2 s} \right], \\
 \psi_{\max} &= \frac{1}{2s} \left[s + m_{Q'}^2 - 4m_Q^2 + \sqrt{(s + m_{Q'}^2 - 4m_Q^2)^2 - 4m_{Q'}^2 s} \right]. \tag{2.11}
 \end{aligned}$$

As has already been noted, QCD sum rules for the masses and residues of the triply heavy baryons can be obtained by matching the two representations of the correlation function for each structure and applying the Borel transformation and continuum subtraction to suppress the contributions coming from the higher states and continuum, as the result of which we get,

$$\begin{aligned}
 \lambda_B^2 e^{-m_B^2/M^2} &= \int_{s_{\min}}^{s_0} ds \rho_1(s) e^{-s/M^2}, \\
 \lambda_B^2 m_B e^{-m_B^2/M^2} &= \int_{s_{\min}}^{s_0} ds \rho_2(s) e^{-s/M^2}, \tag{2.12}
 \end{aligned}$$

where M^2 and s_0 are Borel mass parameter and continuum threshold, respectively, and $s_{\min} = (2m_Q + m_{Q'})^2$. By eliminating the residues from the above equations, we can calculate the masses of the baryons from either one of the following expressions,

$$m_B^2 = \frac{\int_{s_{\min}}^{s_0} ds s \rho_i(s) e^{-s/M^2}}{\int_{s_{\min}}^{s_0} ds \rho_i(s) e^{-s/M^2}}, \quad i = 1 \text{ or } 2, \tag{2.13}$$

$$m_B = \frac{\int_{s_{\min}}^{s_0} ds \rho_2(s) e^{-s/M^2}}{\int_{s_{\min}}^{s_0} ds \rho_1(s) e^{-s/M^2}}. \tag{2.14}$$

3 Numerical results

Now we are ready to analyze numerically the sum rules obtained in the previous section and calculate the numerical values of the masses and residues of the triply heavy spin-1/2 baryons. For this aim we take the quark masses as their pole values $m_b = (4.8 \pm 0.1)$ GeV and $m_c = (1.46 \pm 0.05)$ GeV [24], as well as their \overline{MS} values $\bar{m}_b(\bar{m}_b) = (4.16 \pm 0.03)$ GeV

and $\bar{m}_c(\bar{m}_c) = (1.28 \pm 0.03) \text{ GeV}$ [25]. For the numerical value of the gluon condensate we use $\langle g_s^2 GG \rangle = 4\pi^2(0.012 \pm 0.004) \text{ GeV}^4$ [24].

The sum rules obtained in the previous section incorporate also three auxiliary parameters whose working regions are to be determined. These parameters are the Borel mass parameter M^2 , the continuum threshold s_0 and the general parameter β enrolled to the general current of the baryons under consideration. The working regions of these parameters are found such that the variations in the values of the masses and residues are very weak with respect to their running values.

The continuum threshold s_0 is not completely arbitrary and its value is related to the energy of the first excited state. We do not have adequate information about the first excited states of the baryons under consideration, but our analysis shows that when we choose the continuum threshold in the intervals $s_0 = (140 - 148) \text{ GeV}^2$ and $s_0 = (74 - 81) \text{ GeV}^2$, respectively for the Ω_{bbc} and Ω_{ccb} baryons, the results very weakly depend on s_0 in the case of pole quark masses. While in the case of \overline{MS} values of the quark masses, the working regions for the continuum threshold are obtained as $s_0 = (117 - 125) \text{ GeV}^2$ and $s_0 = (64 - 70) \text{ GeV}^2$ for the baryons Ω_{bbc} and Ω_{ccb} , respectively.

Now we proceed to find the working region for the Borel mass parameter M^2 . The upper bound on this parameter is found by demanding that the pole contribution is high compared to the contributions of the continuum and higher states. This means that the condition,

$$\frac{\int_{s_{\min}}^{s_0} \rho(s) e^{-s/M^2}}{\int_{s_{\min}}^{\infty} \rho(s) e^{-s/M^2}} > 1/2, \tag{3.1}$$

should be satisfied, which leads to the following upper values for M^2 :

$$M_{\max}^2 = \begin{cases} 22 \text{ GeV}^2, & \text{for } \Omega_{bbc} \\ 18 \text{ GeV}^2, & \text{for } \Omega_{ccb}. \end{cases} \tag{3.2}$$

The lower bound on M^2 is calculated requiring that the contribution of the perturbative part exceeds the nonperturbative contributions. From this restriction we obtain

$$M_{\min}^2 = \begin{cases} 12 \text{ GeV}^2, & \text{for } \Omega_{bbc} \\ 9 \text{ GeV}^2, & \text{for } \Omega_{ccb}. \end{cases} \tag{3.3}$$

Our final task is to determine the working region for the auxiliary parameter β . Rather than discussing the variations of the physical observables with respect to this parameter in the interval $(-\infty, +\infty)$, we find it more convenient defining $\beta = \tan\theta$ and look for the variations with respect to $\cos\theta$ in the interval $-1 \leq \cos\theta \leq 1$. Our numerical results show that in the domains $-0.5 \leq \cos\theta \leq -0.9$ and $0.5 \leq \cos\theta \leq 0.9$, the residues depend weakly on $\cos\theta$. Here we should mention that the Ioffe current corresponds to $\cos\theta = -0.71$ and lies inside the reliable region. Note also that, the masses show a very good stability with

	This work (\not{I})	This work (I)	[20]	[12]	[13]	[19]	[14]
Ω_{bbc}	11.73 ± 0.16	11.71 ± 0.16	11.50 ± 0.11	11.139	11.280	10.30 ± 0.10	11.535
Ω_{ccb}	8.50 ± 0.12	8.48 ± 0.12	8.23 ± 0.13	7.984	8.018	7.41 ± 0.13	8.245
$\overline{\Omega}_{bbc}$	10.59 ± 0.14	10.56 ± 0.14	10.47 ± 0.12	-	-	-	-
$\overline{\Omega}_{ccb}$	7.79 ± 0.11	7.74 ± 0.11	7.61 ± 0.13	-	-	-	-

Table 2. The masses of the triply heavy spin-1/2 baryons (in units of GeV). For the baryons with over-line, the \overline{MS} values of the quark masses are used.

	This work (\not{I})	This work (I)	[20]
Ω_{bbc}	0.53 ± 0.17	0.45 ± 0.15	0.68 ± 0.15
Ω_{ccb}	0.38 ± 0.13	0.30 ± 0.10	0.47 ± 0.10
$\overline{\Omega}_{bbc}$	0.85 ± 0.28	0.65 ± 0.22	0.68 ± 0.15
$\overline{\Omega}_{ccb}$	0.56 ± 0.18	0.38 ± 0.13	0.47 ± 0.10

Table 3. The residues of the triply heavy spin-1/2 baryons (in units of GeV^3). For the baryons with over-line, the \overline{MS} values of the quark masses are used.

respect to $\cos\theta$ in the whole allowed region, whose sum rules are defined as the ratio of two expressions including β in eqs. (2.13) and (2.14).

Considering the working regions of the auxiliary parameters we obtain the numerical values for the masses and residues of the triply heavy spin-1/2 baryons as presented in tables 2 and 3 for both structures. For comparison we also present the numerical predictions of other theoretical approaches such as the modified bag model [12], relativistic quark model [13], non-relativistic quark model [14] and QCD sum rules for the Ioffe current [19, 20] in the same tables. As far as the masses are considered, our central value results are slightly higher than the other predictions. The closest results to our predictions are the results of the non-relativistic quark model [14] and QCD sum rules with the Ioffe current [20], respectively. The lower predictions for the masses belong, respectively, to QCD sum rules with the Ioffe current [19] and the modified bag model [12]. From table 2 we see that the two structures in our case give approximately the same results. This table also shows that the results depend on the quarks masses considerably and change (9-10)% when one proceeds from the pole to the \overline{MS} scheme mass parameters. Here, we should mention that considering eq. (2.14) does not affect considerably the results of masses presented in table 2.

In the case of the residues, in contrast to the predictions given in [20], our results depend on the quark masses in such a way that when we switch from the pole to the \overline{MS} scheme quark mass parameters, our results change (21-37)%. This is an expected result since the residues depend more on quark masses in comparison with the baryon masses. From table 3 it is also clear that the results depend on the choice of the structure. The structure I gives the results (15-30)% lower compared to those of the structure \not{I} . In the case of the pole masses of the quarks, our predictions on the residues are considerably smaller in comparison with those of the [20]. The maximum difference between two works is observed for the residue of the Ω_{ccb} baryon obtained from the I structure, which is

approximately 36%. For the residues in \overline{MS} scheme, our results are very close to those of the [20] for the structure I and $\overline{\Omega}_{bbc}$, while the maximum difference of 23% between predictions of two studies belongs to the $\overline{\Omega}_{ccb}$ baryon and also the structure I .

In conclusion, we calculated the masses and residues of the triply heavy spin-1/2 baryons using the most general form of their interpolating currents in the framework of QCD sum rules. We found the reliable working regions of the auxiliary parameters entered to the mass and residue calculations. Our predictions on the masses are slightly higher than the predictions of the other approaches such as, the modified bag model, relativistic and non-relativistic quark models as well as QCD sum rules for the Ioffe current. The predictions for the residues we obtained are considerably different compared to the present predictions of the QCD sum rules for the Ioffe current. We hope that the LHC at CERN will provide opportunity to experimental study of these baryons in near future.

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