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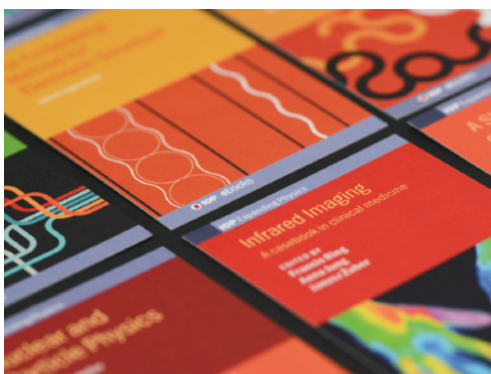
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# Properties of doubly and triply heavy baryons

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**Abstract.** We calculate the mass and residue of the doubly/triply heavy spin-1/2 and spin-3/2 baryons containing two/three heavy b or c quarks in the framework of QCD sum rules. We use the most general interpolating currents in symmetric and anti-symmetric forms with respect to the exchange of heavy quarks, to calculate the two-point correlation functions describing the baryons under consideration. A comparison of the obtained results with the existing experimental data as well as predictions of other theoretical approaches is also made.

## 1. Introduction

The quark model predicts heavy baryons containing single, doubly or triply heavy charm or bottom quarks having either spin-1/2 or spin-3/2. So far, all heavy baryons with single heavy quark have been discovered in the experiments except the  $\Omega_b^*$  baryon with spin-3/2. In the case of doubly heavy baryons only the doubly charmed  $\Xi_{cc}$  baryon has been discovered by SELEX Collaboration [1, 2]. The experimental discovery of the doubly and triply heavy baryons and study of their properties constitute one of the main directions of the physics program at LHC. Hence, theoretical studies on the spectroscopy and decay properties of these baryons can help us in this respect.

## 2. QCD sum rules for the masses and residues of the doubly and triply heavy baryons

In this section we apply the QCD sum rule approach [3] to calculate the spectroscopic properties, namely masses and residues (characterizing the overlap between the baryonic states and the vacuum) of the doubly and triply heavy baryons. For this aim, we start with the following correlation functions:

$$\Pi(q) = i \int d^4x e^{iqx} \langle 0 | \mathcal{T} \{ \eta(x) \bar{\eta}(0) \} | 0 \rangle, \quad (1)$$

and

$$\Pi_{\mu\nu}(q) = i \int d^4x e^{iqx} \langle 0 | \mathcal{T} \{ \eta_\mu(x) \bar{\eta}_\nu(0) \} | 0 \rangle, \quad (2)$$

where  $\eta(x)$  and  $\eta_\mu(x)$  are interpolating currents of the spin-1/2 and spin-3/2 baryons, respectively. The general expressions of the interpolating currents for the spin-1/2 doubly



heavy baryons in their symmetric and anti-symmetric forms can be written as

$$\begin{aligned}\eta^S &= \frac{1}{\sqrt{2}}\epsilon_{abc}\left\{(Q^{aT}Cq^b)\gamma_5Q^c + (Q'^{aT}Cq^b)\gamma_5Q^c + \beta(Q^{aT}C\gamma_5q^b)Q^c + \beta(Q'^{aT}C\gamma_5q^b)Q^c\right\}, \\ \eta^A &= \frac{1}{\sqrt{6}}\epsilon_{abc}\left\{2(Q^{aT}CQ'^b)\gamma_5q^c + (Q^{aT}Cq^b)\gamma_5Q^c - (Q'^{aT}Cq^b)\gamma_5Q^c + 2\beta(Q^{aT}C\gamma_5Q'^b)q^c\right. \\ &\quad \left.+ \beta(Q^{aT}C\gamma_5q^b)Q^c - \beta(Q'^{aT}C\gamma_5q^b)Q^c\right\},\end{aligned}\quad (3)$$

where  $\beta$  is an arbitrary auxiliary parameter. The case,  $\beta = -1$  corresponds to the Ioffe current. Here  $C$  stands for the charge conjugation operator,  $T$  denotes the transposition,  $a$ ,  $b$ , and  $c$  are color indices; and  $Q^{(\prime)}$  and  $q$  correspond to the heavy and light quarks fields, respectively. The interpolating current with the light quark  $u$  or  $d$  corresponds to the  $\Xi_{QQq}$ , and with  $s$  to the  $\Omega_{QQq}$  baryons, respectively. Here, we would like to note that in the symmetric part, both heavy quarks may be identical or different, but in the anti-symmetric part two heavy quarks must be different.

The interpolating current for doubly heavy baryons with spin-3/2 is written as

$$\eta_\mu = \frac{1}{\sqrt{3}}\epsilon^{abc}\left\{(q^{aT}C\gamma_\mu Q^b)Q^c + (q^{aT}C\gamma_\mu Q'^b)Q^c + (Q^{aT}C\gamma_\mu Q'^b)q^c\right\}, \quad (4)$$

where the quark content of the doubly heavy spin-3/2 baryons is shown in Table 1.

**Table 1.** The quark content of the spin-3/2 doubly heavy baryons.

baryon	Light quark $q$	Heavy quark $Q$	Heavy quark $Q'$
$\Xi_{QQ}^*$	$u$ or $d$	$b$ or $c$	$b$ or $c$
$\Omega_{QQ}^*$	$s$	$b$ or $c$	$b$ or $c$
$\Xi_{QQ'}^*$	$u$ or $d$	$b$	$c$
$\Omega_{QQ'}^*$	$s$	$b$	$c$

The interpolating current for the triply heavy spin-1/2 baryons can be written as

$$\eta_{QQQ'} = 2\epsilon_{abc}\left\{(Q^{aT}CQ'^b)\gamma_5Q^c + \beta(Q^{aT}C\gamma_5Q'^b)Q^c\right\}, \quad (5)$$

where the heavy  $Q$  and  $Q'$  quarks contents of the triply heavy baryons predicted by the quark model is given in Table 2. From the current given in Eq. (5) one can formally obtain the interpolating current of the proton (neutron) by replacing  $Q \rightarrow u$  and  $Q' \rightarrow d$  ( $Q \rightarrow d$  and  $Q' \rightarrow u$ ). Finally, the interpolating field for the triply heavy spin-3/2 baryons can be written as

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

Baryon	$Q$	$Q'$
$\Omega_{bbc}$	$b$	$c$
$\Omega_{ccb}$	$c$	$b$

$$\eta_\mu = \frac{1}{\sqrt{3}}\epsilon^{abc}\{2(Q^{aT}C\gamma_\mu Q^b)Q^c + (Q^{aT}C\gamma_\mu Q^b)Q'^c\}, \quad (6)$$

where the quark contents for all members of the triply heavy spin-3/2 baryons are given in Table 3.

**Table 3.** The quark contents of the triply heavy spin-3/2 baryons.

Baryon	$Q$	$Q'$
$\Omega_{bbc}^*$	$b$	$c$
$\Omega_{ccb}^*$	$c$	$b$
$\Omega_{bbb}^*$	$b$	$b$
$\Omega_{ccc}^*$	$c$	$c$

According to the general philosophy of the method, the correlation functions in Eqs. (1) and (2) can be calculated in two different ways. On the hadronic side, they are calculated in terms of the hadronic parameters, while on the QCD side they are evaluated in terms of QCD degrees of freedom. Matching these two representations, then, gives us QCD sum rules for the masses and residues of the baryons 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. These procedures introduce two more auxiliary parameters, the Borel mass parameter  $M^2$  and continuum threshold  $s_0$ . We determine their working regions such that the physical quantities depend weakly on these parameters. For details of calculations see [4, 5, 6, 7].

### 3. Numerical results and discussion

The numerical results for the masses and residues of the doubly and triply heavy baryons obtained from QCD sum rules are depicted in this section. Note that because of the restrictions in number of pages of this article, we only show the results of sum rules for the masses and residues of the doubly heavy baryons in tables 4 and 5 as examples. In these tables, we also present predictions of other non-perturbative approaches as well as existing experimental data.

When we look at tables 4 and 5, we see that our prediction on the mass of the  $\Xi_{cc}$  baryon is in a good consistency with the only existing experimental data provided by SELEX Collaboration. Our results on the masses of doubly heavy baryons are mainly in good consistency with the predictions of other non-perturbative approaches like different quark models within the errors. In the case of residues, our predictions are comparable with the results of [9] within the errors, but considerably differ from those of [8]. These differences can be attributed to the point that [8] uses different interpolating current and obtains different spectral densities compared to our results (for more discussion see [4]). Our numerical calculations on the masses and residues of the doubly heavy spin-3/2 [5], triply heavy spin-1/2 [6] as well as triply heavy spin-3/2 [7] also show that our predictions on the masses are mainly in good consistency with the predictions of other non-perturbative approaches, but in the case of residue, somehow we see some differences between our results and existing predictions in the literature. Considering the recent progress at different hadron colliders especially LHC, we hope that we will have more experimental data on these baryons, whose comparison with the predictions of theoretical works can give us valuable information not only about the internal structures of these baryons but also about the perturbative and non-perturbative aspects of QCD.

**Table 4.** The mass of the doubly heavy spin-1/2 baryons (in units of  $GeV$ ). The numbers inside the parentheses show the uncertainties.

Baryon	Present work	[8]	[9]	[10]	[11]	[12]	Exp [13]
$\Xi_{bb}$	9.96(0.90)	9.78(0.07)	10.17(0.14)	9.94(0.91)	10.202	—	—
$\Omega_{bb}$	9.97(0.90)	9.85(0.07)	10.32(0.14)	9.99(0.91)	10.359	—	—
$\Xi_{bc}$	6.72(0.20)	6.75(0.05)	—	6.86	6.933	7.053	—
$\Omega_{bc}$	6.75(0.30)	7.02(0.08)	—	6.864	7.088	7.148	—
$\Xi_{cc}$	3.72(0.20)	4.26(0.19)	3.57(0.14)	3.52(0.06)	3.620	3.676	3.5189(0.0009)
$\Omega_{cc}$	3.73(0.20)	4.25(0.20)	3.71(0.14)	3.53(0.06)	3.778	3.787	—
$\Xi'_{bc}$	6.79(0.20)	6.95(0.08)	—	—	6.963	7.062	—
$\Omega'_{bc}$	6.80(0.30)	7.02(0.08)	—	—	7.116	7.151	—

**Table 5.** The residues of the doubly heavy spin-1/2 baryons (in units of  $GeV^3$ ).

Baryon	Present work	[8]	[9]
$\Xi_{bb}$	0.44(0.08)	$0.067 \div 0.057$	0.252(0.064)
$\Omega_{bb}$	0.45(0.08)	—	0.311(0.077)
$\Xi_{bc}$	0.28(0.05)	$0.046 \div 0.021$	—
$\Omega_{bc}$	0.29(0.05)	—	—
$\Xi_{cc}$	0.16(0.03)	$0.042 \div 0.026$	0.115(0.027)
$\Omega_{cc}$	0.18(0.04)	—	0.138(0.030)
$\Xi'_{bc}$	0.30(0.05)	—	—
$\Omega'_{bc}$	0.31(0.06)	—	—

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