Properties of doubly heavy spin-$\frac{1}{2}$ baryons: The ground and excited states

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abstract

We determine the masses and residues of the ground and excited spin-$\frac{1}{2}$ baryons consist of two heavy b or c quark utilizing the QCD sum rule formalism. In the calculations, we consider the nonperturbative operators up to ten mass dimensions in order to increase the accuracy compared to the previous calculations. We report the obtained results for both the symmetric and antisymmetric currents defining the doubly heavy baryons of the ground state (1S), first orbitally excited state (1P) and first radially excited state (2S). We compare our results with the predictions of other nonperturbative approaches as well as existing experimental data which is available only for the ground state of Ξ_{cc} channel. These predictions can help the experimental groups in their searches for all members of the doubly heavy baryons in their ground and exited states.

Introduction

Investigation of the properties of the doubly heavy baryons is an important area in particle physics. For a while, scientists were unable to observe baryons consisting of two heavy quarks, posing a longstanding puzzle within the quark model [1]. However, a breakthrough was made in 2002 by the SELEX collaboration with the discovery of $\Xi_{cc}^+(3520)$ in the pD^+K^- decay channel [2], confirmed by the same experiment in 2005 [3]. In 2017, the LHCb collaboration announced the discovery of $\Xi_{cc}^{++}(3621)$ through the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$decay channel [5], confirmed by the same collaboration in 2018[6]. Researches have been conducted based on these discoveries to determine the properties of the doubly heavy baryons within various methods. In this study, we calculate the masses and residues of the doubly heavy baryons in their ground and exited states within the QCD sum rule formalism. The QCD sum rule method follows a standard prescription, where a correlation function is evaluated through two distinct approaches: physical side and QCD side [7, 8]. QCD sum rules for the physical quantities are obtained by matching the results of both sides and considering the coefficients of the same Lorentz structures. To start the calculation, we need to consider the two-point correlation function as following form:

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

where $\eta(x)$ represents the interpolating current of the doubly heavy baryons and $\mathcal{T}$ is the time ordering operator. By inserting the interpolating current of symmetric and antisymmetric of these baryons and after applying the Wick's theorem and conducting all contractions of the quark fields, we obtain the subsequent expression in relation to the heavy and light quarks propagators. There are three auxiliary parameters, namely Borel parameter M^2, threshold parameter s_0 and arbitrary mixing parameter t. They are obtained from the analysis of results based on the standard criteria of the QCD sum rule method. These criteria include weak dependence of the results on auxiliary parameters, pole dominance and convergence of the OPE.

Results

Based on our analysis, we have observed that there is only a weak dependence between the physical quantities and the auxiliary parameters in the given windows for M^2 and s_0 in table 1. The results demonstrate a high level of stability in relation to the Borel parameter and continuum threshold within their respective working regions for all baryons. The principal sources of uncertainties in our numerical outcomes are due to the uncertainties with respect to the auxiliary parameters and errors of other input parameters. After determination of the range of auxiliary parameters, we present the mass and residue of the doubly heavy baryons, obtained through numerical analyses in table 1.

Baryon	State	M^2 (GeV^2)	s_0 (GeV^2)	Mass (GeV)	Residue (GeV^3)
Ξ_{cc}	$\Xi_{cc}(\frac{1}{2}^+)(1S)$	$3.00-5.50$	$3.87^2-4.24^2$	3.69 ± 0.10	0.16 ± 0.04
	$\Xi_{cc}(\frac{1}{2}^-)(1P)$	$3.00-5.50$	$4.37^2-4.74^2$	$3.91^{+0.09}_{-0.11}$	0.18 ± 0.03
	$\Xi_{cc}(\frac{1}{2}^+)(2S)$	$3.00-5.50$	$4.87^2-5.24^2$	4.04 ± 0.08	0.19 ± 0.03
Ξ_{bc}	$\Xi_{bc}(\frac{1}{2}^+)(1S)$	$6.00-9.00$	$6.92^2-7.21^2$	$6.73^{+0.14}_{-0.13}$	0.29 ± 0.06
	$\Xi_{bc}(\frac{1}{2}^-)(1P)$	$6.00-9.00$	$7.42^2-7.71^2$	6.94 ± 0.13	$0.32^{+0.06}_{-0.04}$
	$\Xi_{bc}(\frac{1}{2}^+)(2S)$	$6.00-9.00$	$7.92^2-8.21^2$	7.12 ± 0.14	0.33 ± 0.06
Ξ_{bb}	$\Xi_{bb}(\frac{1}{2}^+)(1S)$	$10.00-15.00$	$10.58^2-10.86^2$	9.97 ± 0.19	$0.45^{+0.09}_{-0.08}$
	$\Xi_{bb}(\frac{1}{2}^-)(1P)$	$10.00-15.00$	$11.08^2-11.36^2$	10.25 ± 0.18	$0.60^{+0.09}_{-0.08}$
	$\Xi_{bb}(\frac{1}{2}^+)(2S)$	$10.00-15.00$	$11.58^2-11.86^2$	$10.33^{+0.18}_{-0.19}$	$0.70^{+0.09}_{-0.10}$
Ω_{cc}	$\Omega_{cc}(\frac{1}{2}^+)(1S)$	$3.00-5.50$	$3.89^2-4.26^2$	3.70 ± 0.09	0.17 ± 0.04
	$\Omega_{cc}(\frac{1}{2}^-)(1P)$	$3.00-5.50$	$4.39^2-4.76^2$	$3.93^{+010}_{-0.09}$	$0.19^{+0.03}_{-0.04}$
	$\Omega_{cc}(\frac{1}{2}^+)(2S)$	$3.00-5.50$	$4.89^2-5.26^2$	$4.07^{+0.08}_{-0.09}$	$0.20^{+0.04}_{-0.03}$
Ω_{bc}	$\Omega_{bc}(\frac{1}{2}^+)(1S)$	$6.00-9.00$	$6.92^2-7.21^2$	$6.77^{+0.13}_{-0.12}$	0.30 ± 0.05
	$\Omega_{bc}(\frac{1}{2}^-)(1P)$	$6.00-9.00$	$7.42^2-7.71^2$	7.07 ± 0.12	$0.33^{+0.05}_{-0.06}$
	$\Omega_{bc}(\frac{1}{2}^+)(2S)$	$6.00-9.00$	$7.92^2-8.21^2$	7.20 ± 0.13	0.35 ± 0.06
Ω_{bb}	$\Omega_{bb}(\frac{1}{2}^+)(1S)$	$10.00-15.00$	$10.58^2-10.86^2$	9.98 ± 0.18	$0.46^{+0.09}_{-0.08}$
	$\Omega_{bb}(\frac{1}{2}^-)(1P)$	$10.00-15.00$	$11.08^2-11.36^2$	10.31 ± 0.19	0.63 ± 0.09
	$\Omega_{bb}(\frac{1}{2}^+)(2S)$	$10.00-15.00$	$11.58^2-11.86^2$	10.45 ± 0.18	$0.75^{+0.08}_{-0.09}$
Ξ'_{bc}	$\Xi'_{bc}(\frac{1}{2}^+)(1S)$	$6.00-9.00$	$6.92^2-7.21^2$	6.81 ± 0.11	0.31 ± 0.05
	$\Xi'_{bc}(\frac{1}{2}^-)(1P)$	$6.00-9.00$	$7.42^2-7.71^2$	$6.99^{+0.13}_{-0.12}$	$0.34^{+0.04}_{-0.05}$
	$\Xi'_{bc}(\frac{1}{2}^+)(2S)$	$6.00-9.00$	$7.92^2-8.21^2$	$7.15^{+0.14}_{-0.13}$	0.36 ± 0.06
Ω'_{bc}	$\Omega'_{bc}(\frac{1}{2}^+)(1S)$	$6.00-9.00$	$6.92^2-7.21^2$	6.82 ± 0.12	0.32 ± 0.06
	$\Omega'_{bc}(\frac{1}{2}^-)(1P)$	$6.00-9.00$	$7.42^2-7.71^2$	$7.03^{+0.13}_{-0.12}$	0.35 ± 0.06
	$\Omega'_{bc}(\frac{1}{2}^+)(2S)$	$6.00-9.00$	$7.92^2-8.21^2$	$7.24^{+0.14}_{-0.13}$	$0.38^{+0.06}_{-0.07}$

Table 1: The auxiliary parameters and the outcomes of the masses and residues for the ground, first orbitally excited and first radially excited states.

Conclusion

The investigation of the properties of the doubly heavy baryons represents a promising area in particle physics. To study any type of interactions/decays of the doubly heavy baryons, we need the exact values of the masses and residues of these baryons. The values of the spectroscopic parameters calculated from theory can also guide experimental groups to search for the unseen baryon members predicted by the quark model. For this purpose, we determined the spectroscopic parameters of the doubly heavy baryons with a higher accuracy in the ground, first orbitally and first radially excited states. Our predictions may help experimental groups in the course of their search for the unseen members of the doubly heavy baryons. They may also be checked by other nonperturbative approaches in future.

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