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Study of the spectra and decay widths of singly heavy baryons

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Abstract. We present a study of the spectra and strong decay widths of singly heavy baryons. The masses of singly heavy baryons up to the D-wave are calculated within a constituent quark model, employing the three-quark and quark-diquark schemes. In this contribution, we discuss the possible assignment of the recently discovered $\Omega_c(3327)^0$, $\Xi_b(6327)^0$, and $\Xi_b(6333)^0$ as D-wave excited states in the charm and bottom sectors, respectively. Additionally, we discuss why the presence or absence of the ρ-mode excitations in the experimental spectrum is the key to distinguishing between the quark-diquark and three-quark behaviors.

1 Introduction

Recent advancements in the understanding of singly heavy baryons have been achieved through the application of non-relativistic quark models, QCD sum rules, and lattice QCD [1]. However, despite these efforts, no existing model comprehensively describes the complete baryon spectrum, decay widths, and internal quantum structure. On the experimental front, observations from the LHCb and Belle experiments have consistently identified various charmed baryon states, including but not limited to $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, $\Omega_c(3119)$ (observed only by LHCb), and $\Omega_c(3188)$ (reported in references [2, 3]). The LHCb experiment has reported the observation of $\Xi_c(2923)^0$, $\Xi_c(2939)^0$, and $\Xi_c(2965)^0$ states [4]. In the bottom sector, the LHCb collaboration has recently reported the observation of singly bottom baryons, in 2020, two D-wave Λ_b^0 candidates, the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ baryons [5], in the same year the LHCb collaboration [6] reported the observation of four narrow peaks in the $\Xi_b^0 K^-$ invariant mass spectrum, the $\Omega_b(6316)$, $\Omega_b(6330)$, $\Omega_b(6340)$ and $\Omega_b(6350)$ baryons. Very recently, two new excited states, the $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$ baryons were observed in the $\Xi_c^+ K^-$ invariant-mass spectrum by the LHCb Collaboration [7]. The measured masses and widths of the two newly found states are

$$m[\Omega_c(3185)] = 3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2\text{MeV}, \tag{1}$$

$$\Gamma[\Omega_c(3185)] = 50 \pm 7^{+10}_{-20}\text{MeV}, \tag{2}$$

$$m[\Omega_c(3327)] = 3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2\text{MeV}, \tag{3}$$

$$\Gamma[\Omega_c(3327)] = 20 \pm 5^{+13}_{-1}\text{MeV}. \tag{4}$$

However, the spin-parity quantum numbers of these observed states are waiting to be assigned. These Ω_c baryons were investigated as ordinary baryon in Refs. [8–12] and as hadronic molecular states in Ref. [13–15].

In the bottom sector, the LHCb collaboration reported two narrow resonances, the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, in the $\Lambda_b^0 K^- \pi^+$ mass spectrum [16]. Their masses and decay widths are respectively

$$m[\Xi_b(6327)^0] = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24 \text{ MeV}, \tag{5}$$

$$\Gamma[\Xi_b(6327)^0] = 0.93^{+0.74}_{-0.60} \text{ MeV}, \tag{6}$$

$$m[\Xi_b(6333)^0] = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22 \text{ MeV}, \tag{7}$$

$$\Gamma[\Xi_b(6333)^0] = 0.25^{+0.58}_{-0.25} \text{ MeV}. \tag{8}$$

According to the previous studies of the $\Xi_b^{(\prime)}$ baryon spectrum [17–20], the two newly observed Ξ_b^0 states by LHCb [16] may be λ-mode $1D$ Ξ_b states. In addition, the few works on strong decay properties also supported the two new states as λ-mode $1D$ Ξ_b states with $J^P = 3/2^+$ and $J^P = 5/2^+$ [17, 21, 22].

In the present contribution, we use the model presented in Ref. [23] and its recent application to D-wave singly heavy baryons [17, 24], with the aim of discussing the assignment of the $\Omega_c(3327)$, $\Xi_b(6327)$, and $\Xi_b(6333)$ states. The discussion of the assignment of the $\Omega_c(3185)$ baryon, however, is the subject of a subsequent article [25].

2 Three quark model for singly heavy baryons

The mass spectrum of the singly heavy baryons can be described by the mass formula introduced in Ref. [23]:

$$\begin{aligned} M \;=\; & \sum_{i=1}^{3} m_i + \omega_\rho n_\rho + \omega_\lambda n_\lambda + AS(S+1) + B\frac{1}{2}\left[J(J+1) - L(L+1) - S(S+1)\right] \\ & + EI(I+1) + G\frac{1}{3}\left[p(p+3) + q(q+3) + pq\right], \end{aligned} \tag{9}$$

where, n_ρ and n_λ represent the quanta in the ρ- and λ-oscillator, respectively. The corresponding frequencies share the same spring constant $K_{b/c}$ but have different reduced masses:

$$\omega_\rho = \sqrt{\frac{3K_{b/c}}{m_\rho}} = \sqrt{\frac{6K_{b/c}}{m_1 + m_2}}, \qquad \omega_\lambda = \sqrt{\frac{3K_{b/c}}{m_\lambda}} = \omega_\rho \sqrt{\frac{m_1 + m_2 + m_3}{3m_3}}. \tag{10}$$

The labels L, S, J, and I stand for the orbital angular momentum, spin, total angular momentum, and isospin, respectively. The labels (p, q) denote the $SU(3)$ flavor multiplets:

the flavor sextet is labeled by $(2,0) \equiv \mathbf{6}$, the antitriplet by $(0,1) \equiv \bar{\mathbf{3}}$, the triplet by $(1,0) \equiv \mathbf{3}$, and the singlet by $(0,0) \equiv \mathbf{1}$. The parameters A, B, E and G were determined through a fit for singly charmed baryons in Ref. [24], and for the singly bottom baryons in Ref. [17]. The theoretical results of Ref. [24] for the Ω_c are reported in Fig. 1.

2.1 Quark-diquark scheme for singly heavy baryons

The singly heavy baryons as quark-diquark systems can be described by the mass formula introduced in Ref. [23]

$$\begin{aligned} M^{qD} \;\; = \;\; & m_D + m_{b/c} + \omega_r \, n_r + a_{\rm S} \left[S_{\rm tot}(S_{\rm tot}+1)\right] + a_{\rm SL}\frac{1}{2}\Big[J(J+1) - L_{\rm tot}(L_{\rm tot}+1) \\ & - S_{\rm tot}(S_{\rm tot}+1)\Big] + a_{\rm I}\left[I(I+1)\right] + a_{\rm F}\frac{1}{3}\left[p(p+3) + q(q+3) + pq\right] \; . \end{aligned} \tag{11}$$

where m_D and $m_{b/c}$ are the diquark and heavy quark masses, respectively. The theoretical results of Ref. [24] for the Ω_c within the quark-diquark scheme are reported in Fig. 2.

3 $\Omega_c(3327)^0$, $\Xi_b(6327)^0$, and $\Xi_b(6333)^0$ assignments

We discuss the possible assignment of the recently discovered $\Omega_c(3327)^0$, $\Xi_b(6327)^0$, and $\Xi_b(6333)^0$ as D_λ-wave excited states.

3.1 $\Omega_c(3327)^0$ assignment

In Ref.[24], the three-quark model predicts six $\Omega_c(ssc)$ D_λ-wave states, corresponding to the six D-wave states predicted by the quark-diquark scheme, detailed in Table 1. Based on these results, we observe that the $\Omega_c(3327)^0$, observed by the LHCb Collaboration in the $\Xi_c^+ K^-$ channel [7], can be tentatively assigned to either the $|l_\lambda = 2, l_\rho = 0\rangle$, ${}^2D_{3/2}$ state with a mass of 3306^{+14}_{-14} MeV and a width of $10.6^{+5.3}_{-5.3}$ MeV, or the $|l_\lambda = 2, l_\rho = 0\rangle$, ${}^4D_{1/2}$ state with a mass of 3330^{+25}_{-25} MeV and a width of $16.3^{+8.2}_{-8.0}$ MeV. Both results are compatible with the experimental data, thus the measurement of the quantum numbers of the Ω_c D_λ-wave states is necessary to make a unique assignment. Additionally, it is important to mention that the $\Omega_c(3327)^0$ was observed by the LHCb Collaboration in the $\Xi_c^+ K^-$ channel. However, in Ref. [24], other channels were investigated where the remaining five Ω_c D_λ-wave states can be detected, such as $\Xi_c' K$, $\Xi_c^* K$, $\Omega_c \eta$, and $\Xi_8 D_s^+$. Notably, the $\Xi_8 D_s^+$ channel is identified as the dominant one.

3.2 $\Xi_b(6327)^0$, and $\Xi_b(6333)^0$ assignments

In Ref. [17], the two observed states, $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, by LHCb [16], were assigned as two Ξ_b^0 D_λ excitations with quantum numbers $\mathbf{J}^P = \frac{3}{2}^+$ and $\mathbf{J}^P = \frac{5}{2}^+$, respectively, belonging to the antitriplet configuration, this result is compatible with the previous identification reported in Ref. [20]. The predicted decay width of the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ states given in Ref. [17] is in good agreement with the experimental data.

4 Discussion and conclusions

In Ref. [24], it was provided the mass spectrum and strong decay width predictions for the Ω_c up to D-wave states. By comparing Fig. 1 with 2, one can observe that in the quark-diquark scheme, there are much less missing singly charm baryons. The difference in the number of

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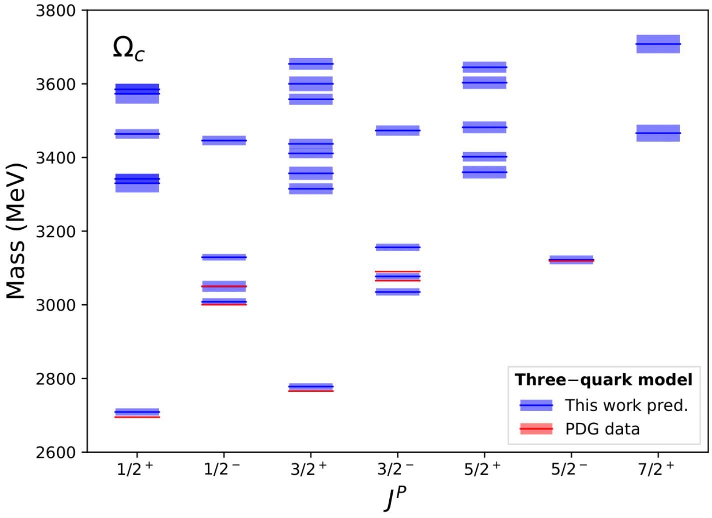

Figure 1. Ω_c mass spectra and tentative quantum number assignments based on the three-quark model Hamiltonian of Eq. 9. The theoretical predictions and their uncertainties (blue lines and bands) are compared with the experimental results PDG [26] (red lines and bands). Figure taken from Ref. [24] APS copyright.

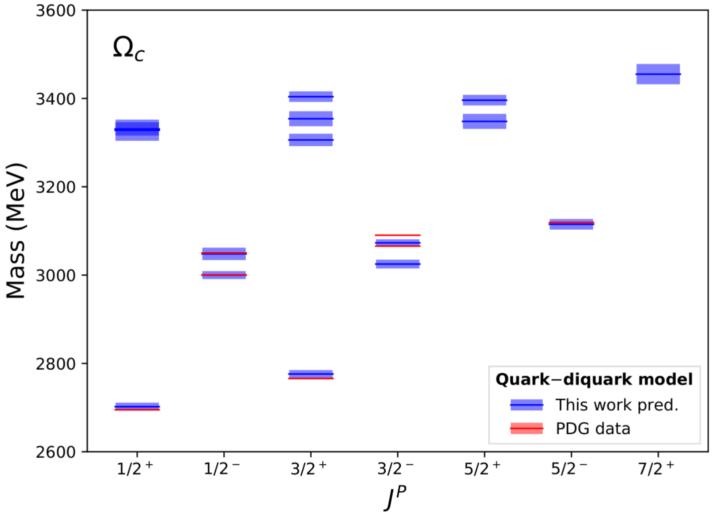

Figure 2. Ω_c mass spectra and tentative quantum number assignments based on the quark-diquark model Hamiltonian of Eq. 11. the theoretical predictions and their uncertainties (blue lines and bands) are compared with the experimental results PDG [26] (red lines and bands). Figure taken from Ref. [24] APS copyright.

Table 1. $\Omega_c(ssc)$ D_λ-wave states. Orbital state (first column), quantum number assignments (second column), theoretical masses using the three-quark model taken from Ref. [24] (third column), theoretical masses calculated using the diquark framework taken from Ref. [24] (fourth column), and strong decay widths taken from Ref. [24] (fifth column), APS copyright. An ssc state is characterized by total angular momentum $\mathbf{J} = \mathbf{l}_\rho + \mathbf{l}_\lambda + \mathbf{S}_{\rm tot}$, where $\mathbf{S}_{\rm tot} = \mathbf{S}_\rho + \frac{1}{2}$, and flavor multiple $\mathcal{F}$.

$\Omega_c(ssc)$ $\mathcal{F} = \mathbf{6}_{\rm f}$	$^{2S+1}L_J$	Three-quark Predicted Mass (MeV)	Quark-diquark Predicted Mass (MeV)	Predicted Γ_{tot} (MeV)
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^2D_{3/2}$	3315^{+15}_{-14}	3306^{+14}_{-14}	$10.6^{+5.3}_{-5.3}$
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^2D_{5/2}$	3360^{+17}_{-16}	3348^{+17}_{-17}	$24.4^{+12.0}_{-11.9}$
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^4D_{1/2}$	3330^{+25}_{-25}	3328^{+24}_{-23}	$16.3^{+8.2}_{-8.0}$
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^4D_{3/2}$	3357^{+18}_{-19}	3354^{+17}_{-17}	$30.4^{+14.8}_{-14.9}$
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^4D_{5/2}$	3402^{+13}_{-13}	3396^{+12}_{-12}	$62.3^{+31.0}_{-31.1}$
$\vert l_\lambda = 2, l_\rho=0\rangle$	$^4D_{7/2}$	3466^{+23}_{-23}	3455^{+23}_{-23}	$123.0^{+61.4}_{-62.1}$

predicted states arises from the fact that ρ-mode states vanish in the quark-diquark scheme. It is worth mentioning that the observed states are tentatively identified as λ-mode excited states. If the ρ-mode states are not observed in experiments, it would suggest that the heavy singly heavy baryons are effectively quark-diquark systems.

In summary, the most recent data from LHCb has broadened our understanding of the excited singly heavy baryons. Nevertheless, most of the states are yet to be identified, and a definitive assignment awaits the measurement of quantum numbers. The experimental search for these missing states, completing the multiplet, is crucial. Taking the example of the $\Omega_c(ssc)$ D_λ-wave states, at least six states are expected, with the currently observed $\Omega_c(3327)^0$ being the only known candidate. Based on the findings of Ref. [24], the remaining five Ω_c D_λ-wave states can be detected in the $\Xi_c' K$, $\Xi_c^* K$, $\Omega_c\eta$, and $\Xi_8 D_s^+$ channels, with the $\Xi_8 D_s^+$ channel being identified as the dominant one.

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