Heavy $\Omega_c$ and $\Omega_b$ baryons in the quark model

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Abstract. In this contribution, we present a study of ground- and excited-state $\Omega_c$ and $\Omega_b$ baryons consisting of two strange quarks and a heavy charm or bottom quark. An analysis in the quark model shows that the recently observed excited $\Omega_c$ and $\Omega_b$ states can be interpreted in terms of $\lambda$-mode excitations.

1. Introduction

In recent years there has been a renewed interest in hadron physics especially concerning hadrons containing heavy (charm or bottom) quarks. The experimental discovery of many new heavy baryons [1] as well as candidates for multiquark configurations like tetraquark and pentaquark states [2, 3] has sparked a large number of studies into the structure of hadrons.

In particular, we mention the discovery of five new $\Omega_c$ states by the LHCb Collaboration in the $\Xi_c^+K^-$ decay channel [4] and the subsequent confirmation of four of these states by the Belle Collaboration [5]: $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3065)$ and $\Omega_c(3090)$. In addition, the $\Omega_c(3188)$, even if not yet confirmed as a genuine resonance for lack of sufficient statistical significance, was seen by both LHCb and Belle, whereas the $\Omega_c(3119)$ was observed only by LHCb, but not by Belle.

Since neither LHCb nor Belle were able to determine angular momenta and parities, the assignment of quantum numbers is model dependent. Several different assignments exist in the literature, see e.g. [6, 7, 8, 9, 10, 11]. In particular, for the $\Omega_c(3119)$ there exists a variety of spin and parity assignments: $J^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$ [8], $\frac{5}{2}^+$ [9], $\frac{3}{2}^+$ or $\frac{5}{2}^-$ [6].

The aim of this contribution is to present a quark model study of ground- and excited-state $\Omega_c$ baryons, and to show that they can be interpreted in terms of $\lambda$-mode excitations. The analysis is based both on masses and decay widths. A similar study is carried out for $\Omega_b$ baryons which subsequently was confirmed by new experimental data from the LHCb Collaboration [12].
2. $\Omega_c$ and $\Omega_b$ baryons

In the quark model, $\Omega_c$ and $\Omega_b$ baryons correspond to $ssQ$ configurations consisting of two strange quarks and one heavy quark, $Q = c$ and $b$, respectively. In this contribution we consider a harmonic oscillator quark model with a spin, spin-orbit, isospin and flavor dependent terms according to Ref. [11]

$$H = H_{ho} + A \vec{S} \cdot \vec{S} + B \vec{L} \cdot \vec{S} + E \vec{I} \cdot \vec{I} + G C_{2SU(3)}. \tag{1}$$

The harmonic oscillator quark model for $ssQ$ baryons with two equal masses $m_1 = m_2 = m_s$ different from the third $m_3 = m_Q$ is given by [13]

$$H_{ho} = \sum_i \left( m_i + \frac{p_i^2}{2m_i} \right) + \frac{1}{2} C \sum_{i<j} (\vec{r}_i - \vec{r}_j)^2$$

$$= 2m_s + m_Q + \frac{P^2}{2(2m_s + m_Q)} + \frac{p_\rho^2}{2m_\rho} + \frac{p_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\rho \omega_\rho^2 \rho^2 + \frac{1}{2} m_\lambda \omega_\lambda^2 \lambda^2, \tag{2}$$

where we have made a change of variables to relative Jacobi coordinates and the center-of-mass coordinate

$$\vec{\rho} = (\vec{r}_1 - \vec{r}_2)/\sqrt{2},$$
$$\vec{\lambda} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)/\sqrt{6},$$
$$\vec{R} = \frac{m_s(\vec{r}_1 + \vec{r}_2) + m_Q\vec{r}_3}{2m_s + m_Q}. \tag{3}$$

The reduced masses are given by $m_\rho = m_s$ and $m_\lambda = 3m_s m_Q/(2m_s + m_Q)$, and the frequencies of the oscillators in the $\rho$ and the $\lambda$ coordinate by $\omega_\rho = \sqrt{3C/m_\rho}$ and $\omega_\lambda = \sqrt{3C/m_\lambda}$. For equal masses the two frequencies become the same, $\omega_\rho = \omega_\lambda$. For the case of interest in this contribution, $qqQ$ baryons with two light and one heavy quark, the frequencies satisfy $\omega_\lambda < \omega_\rho$. For $QQq$ baryons the situation is reversed, $\omega_\rho < \omega_\lambda$.

The parameters in the Hamiltonian of Eq. (1) were obtained by studying the single-charm baryons, $\Sigma_c, \Lambda_c$ and $\Xi_c$, and the single-bottom baryons, $\Sigma_b$ and $\Lambda_b$ [11]. The results are given in Table 1. We note, that the $ssQ$ configurations in Table 2 all have the same isospin $I = 0$ and all belong to the flavor sextet. Moreover, the sum of the quark masses, $2m_s + m_Q$, is the same for

![Figure 1. Excitation modes, $\rho$ and $\lambda$.](image)
Table 1. Parameter values for $\Omega_c$ and $\Omega_b$ baryons ($ssQ$ baryons with $Q = c$ and $Q = b$, respectively) [11].

|       | $Q = c$ | $Q = b$ |
|-------|---------|---------|
| $m_s$ | 450     | 450     |
| $m_Q$ | 1605    | 4920    |
| $C$   | 0.0328  | 0.0235  |
| $A$   | 21.54 ± 0.37 | 6.73 ± 1.63 |
| $B$   | 23.91 ± 0.31 | 5.15 ± 0.33 |
| $E$   | 30.34 ± 0.23 | 26.00 ± 1.80 |
| $G$   | 54.37 ± 0.58 | 70.91 ± 0.49 |

Table 2. Classification of $ssQ$ baryons.

| State | Wave function | $(n_\rho, n_\lambda)$ | $L$ | $J^P$   |
|-------|---------------|------------------------|-----|---------|
| $^2\Omega_Q$ | $ssQ [\psi_0 \times \chi_\lambda]$ | $(0, 0)$ | 0 | $\frac{1}{2}^+$ |
| $^4\Omega_Q$ | $ssQ [\psi_0 \times \chi_S]$ | $(0, 0)$ | 0 | $\frac{3}{2}^+$ |
| $^2\lambda_J(\Omega_Q)$ | $ssQ [\psi_\lambda \times \chi_\lambda]$ | $(0, 1)$ | 1 | $\frac{1}{2}^-, \frac{3}{2}^-$ |
| $^4\lambda_J(\Omega_Q)$ | $ssQ [\psi_\lambda \times \chi_S]$ | $(0, 1)$ | 1 | $\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ |
| $^2\rho_J(\Omega_Q)$ | $ssQ [\psi_\rho \times \chi_\rho]$ | $(1, 0)$ | 1 | $\frac{1}{2}^-, \frac{3}{2}^-$ |
Figure 2. $\Omega_c$ mass spectrum with tentative quantum number assignments. Quark model [11] (red dots), LHCb [4] (blue line), Belle [5] (violet line) and PDG [1] (black line).

3. Masses and decay widths
In Fig. 2 we show a comparison of the theoretical (red dots) and experimental mass spectrum (blue, violet and black lines) of $\Omega_c$ baryons in combination with a tentative assignment of quantum numbers. The $\Omega_c(3000)$ and $\Omega_c(3065)$ baryons are assigned to the $\lambda$-mode excitation $^{2}\lambda_J(\Omega_Q)$ configuration with $J^P = 1/2^-$ and $3/2^-$, respectively, and the $\Omega_c(3050)$, $\Omega_c(3090)$ and $\Omega_c(3188)$ baryons to the $\lambda$-mode excitation $^{4}\lambda_J(\Omega_Q)$ configuration with $J = 1/2^-$, $3/2^-$ and $5/2^-$, respectively. We find a good agreement between the theoretical mass spectrum and the experimental data. With the exception of the lightest and the heaviest resonant states, $\Omega_c(3000)$ and $\Omega_c(3188)$, respectively, the theoretical masses are in agreement with the data within the experimental error, which is very small (less than 1 MeV). Similarly to Refs. [14, 15, 16], we suggest a molecular interpretation of the $\Omega_c(3119)$ state which was observed by the LHCb [4],

Figure 3. As Fig. 2, but for the $\Omega_b$ mass spectrum.
Table 3. Masses and decay widths of $\Omega_c$ (top) and $\Omega_b$ baryons (bottom). Experimental data taken from [1, 4, 12].

| State          | $M$ (MeV) | $\Gamma$ (MeV) | Exp | Mass (MeV) | $\Gamma_{tot}$ (MeV) |
|----------------|-----------|----------------|-----|------------|----------------------|
| $^2\Omega_c$   | 2702 ± 12 | -              | $\Omega_c$ | 2695.2 ± 1.7 |
| $^4\Omega_c$   | 2767 ± 13 | -              | $\Omega_c$ | 2765.9 ± 2.0 |
| $^2\lambda(\Omega_c)_{1/2}$ | 3016 ± 9  | 0.48           | $\Omega_c(3000)$ | 3000.4 ± 0.2 | 4.5 ± 0.6 ± 0.3 |
| $^4\lambda(\Omega_c)_{1/2}$ | 3045 ± 13 | 1.0            | $\Omega_c(3050)$ | 3050.2 ± 0.1 | < 1.2 |
| $^2\lambda(\Omega_c)_{3/2}$ | 3052 ± 15 | 3.5*           | $\Omega_c(3065)$ | 3065.5 ± 0.3 | 3.5 ± 0.4 ± 0.2 |
| $^4\lambda(\Omega_c)_{3/2}$ | 3080 ± 13 | 1.09           | $\Omega_c(3090)$ | 3090.0 ± 0.5 | 8.7 ± 1.0 ± 0.8 |
| Molecule       |           |                | $\Omega_c(3120)$ | 3119.1 ± 1.0 | < 2.6 |
| $^4\lambda(\Omega_c)_{5/2}$ | 3140 ± 14 | 9.87           | $\Omega_c(3188)$ | 3188 ± 14 | 60 ± 26 |
| $^2\rho(\Omega_c)_{1/2}$ | 3146 ± 12 | 6.28           | n.o. |            |
| $^2\rho(\Omega_c)_{3/2}$ | 3182 ± 12 | 7.04           | n.o. |            |
| $^2\Omega_b$   | 6061 ± 15 | -              | $\Omega_b$ | 6046.1 ± 0.7 |
| $^4\Omega_b$   | 6082 ± 20 | -              | n.o. |            |
| $^2\lambda(\Omega_b)_{1/2}$ | 6305 ± 15 | 0.50           | $\Omega_b(6316)$ | 6315.6 ± 0.6 | < 2.8 ± 4.2 |
| $^2\lambda(\Omega_b)_{3/2}$ | 6313 ± 15 | 1.14           | $\Omega_b(6330)$ | 6330.3 ± 0.6 | < 3.1 ± 4.7 |
| $^4\lambda(\Omega_b)_{1/2}$ | 6317 ± 19 | 2.79           | $\Omega_b(6340)$ | 6339.7 ± 0.6 | < 1.5 ± 1.8 |
| $^4\lambda(\Omega_b)_{3/2}$ | 6325 ± 19 | 0.62           | $\Omega_b(6350)$ | 6349.9 ± 0.6 | < 2.8 ± 3.2 |
| $^4\lambda(\Omega_b)_{5/2}$ | 6338 ± 20 | 4.28           | n.o. |            |
| $^2\rho(\Omega_b)_{1/2}$ | 6452 ± 15 | 4.92           | n.o. |            |
| $^2\rho(\Omega_b)_{3/2}$ | 6460 ± 15 | 3.82           | n.o. |            |

but not by Belle [5]. For this reason, $\Omega_c(3119)$ is not included in Fig. 2.

Until recently, the experimental knowledge on $\Omega_b$ baryons was limited to $\Omega_b^-$ with mass 6046 MeV [1] which we assign as the $^2\Omega_b^-$ quark model state. In Table 3, we show the results of our predictions for the ground- and excited-state $\Omega_b$ baryons [11]. Shortly thereafter, the LHCb Collaboration announced the first observation of excited $\Omega_b^-$ states as four peaks in the $\Xi_b^0 K^-$ mass spectrum [12] with decay widths of the order of a few MeV. In Table 3 we make a comparison between our predictions and the new experimental results. The assignment of quantum numbers is based on the masses.

In Table 3 we also show the results for the strong decays

$$\Gamma(ssc \rightarrow gsc + s\eta) = \Gamma(\Omega_c \rightarrow \Xi_c + \bar{K}) + \Gamma(\Omega_c \rightarrow \Xi_c' + \bar{K}) + \Gamma(\Omega_c \rightarrow \Xi_c'' + \bar{K}),$$

$$\Gamma(ssb \rightarrow gsb + s\eta) = \Gamma(\Omega_b \rightarrow \Xi_b + \bar{K}) + \Gamma(\Omega_b \rightarrow \Xi_b' + \bar{K}) + \Gamma(\Omega_b \rightarrow \Xi_b'' + \bar{K}).$$

The theoretical values were calculated in a $^3P_0$ decay model in which the strength parameter was fitted to the decay of the $\Omega_c(3065)$ baryon. The experimental data correspond to the total decay width, there is no information on branching ratios. Table 3 shows that the theoretical widths which are based on the mass estimates and the quantum number assignments, are compatible with the present experimental data for both the $\Omega_c$ and $\Omega_b$ baryons. The decay widths of both the $\Omega_c$ and $\Omega_b$ states are of the order of a few MeV.
The LHCb Collaboration reported the observation of four excited Ωb baryons [11]. In a quark model analysis like the present one, one would expect, just as for the Ωc baryons, the occurrence of five such states as λ-mode excitations. The ρ-mode excitations arise at a slightly higher mass.

4. Summary and conclusions

In this contribution we showed that the five excited Ω0c states observed by the LHCb Collaboration [4] and later confirmed by the Belle Collaboration [5] can be understood in a very simple manner in the quark model as λ-mode excited states. In addition, one expects two more Ω0c states as ρ-mode excited states, but these have a bit higher mass. Even though these states are decoupled from the Ξc¯K decay channel by selection rules, they can decay into Ξ′c¯K and Ξ′∗c¯K.

The same observations hold for the beauty (or bottom) sector. In the quark model, one predicts the occurrence of five Ω−b states as λ-mode excitations, and two more as ρ-mode excitations. Meanwhile, four excited Ω−b states have been observed by the LHCb Collaboration [12] with masses very close to the predicted values.

Our conclusions are not only based on mass systematics, but also on decay widths. The strong decay widths ΩQ → ΞQK, Ξ′QK, Ξ′∗QK were calculated in a 3P0 model to be of the order of a few MeV, in agreement with the experimental data for the total widths. Since there is no experimental information available on branching ratios, the only constraint we have is that the calculated widths have to be smaller than the experimental values for the total widths.

A final remark concerns the quantum numbers of the Ωc and Ωb states. The spin and parity assignments in Table 3 are based on mass systematics and decay widths. Their values have not (yet) been determined experimentally.

Acknowledgments

This work was supported in part by grant IN101320 from DGAPA-UNAM and by grant 251718 from CONACyT, Mexico. H. G.-T. acknowledges financial support from Consejo Nacional de Ciencia y Tecnología, Mexico.

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