Excited $\Omega$’s as heavy pentaquarks

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Abstract. We briefly summarize recent works on the identification of the excited $\Omega$’s found by the LHCb Collaboration. Within the framework of a pion mean-field approach, the following scenario is the most favorable: While three of the excited $\Omega$’s belong to the excited baryon sextet, two of them with the smaller decay widths can be identified as the members of the anti-decapentaplet which is one of the lowest-lying representations. It implies that these two $\Omega$’s, i.e. $\Omega(3050)$ and $\Omega(3119)$ are most probably the exotic heavy pentaquark baryons.

Keywords: Excited $\Omega$, pentaquarks, pion mean fields, chiral quark-soliton model

1 Introduction

A pentaquark baryon consists of five valence quarks, which was already mentioned by Gell-Mann [1] who christened the fundamental building block of a hadron or the true atom a quark. The LHCb Collaboration reported for the first time the finding of two heavy pentaquarks that were coined as $P_c(4380)$ and $P_c(4450)$ respectively [2,3,4,5]. The valence quark content of these heavy pentaquarks is given $uudc\bar{c}$. They can be considered as resonances involving the $J/\psi$ ($c\bar{c}$) and the proton ($uud$). Yet another interesting finding of five excited $\Omega^*$’s was announced also by the LHCb Collaboration [6], four of which were confirmed by the Belle Collaboration [7].

One can naturally classify them as the members of the excited baryon sextets, since there exist the five sextet representations, once one of the valence quarks are excited to the level with the orbital angular momentum $l = 1$. In the present talk, we will show that this classification is inconsistent with the experimental data and will propose that two of them can be regarded as members of the baryon anti-decapentaplet ($15^{-}$) [8,9], which appear as one of the lowest representations for singly heavy baryons. By the member of the baryon anti-decapentaplet we mean that it is a heavy pentaquark baryon.

The general theoretical framework we employ in this work is a pion mean-field approach, which can be also called as the chiral quark-soliton model ($\chi$QSM).
Mean-field approximations have enjoyed simple but clear understanding of various physical problems in different branches of physics and have been used even in different fields such as applied mathematics, computer sciences, etc. The main idea of the pion mean-field approach is that the quantum fluctuation of the pion field, which can be regarded as the $1/N_c$ corrections in the large $N_c$ expansion, can be suppressed [10]. Then, the pion mean field arises from the classical solution of the equation of motion for the pion around the saddle point [11]. This $\chi$QSM was successfully used to describe numerous properties of the nucleon and SU(3) hyperons, including their static properties and form factors [12] and parton distributions. Recently, the $\chi$QSM was extended to the description of singly heavy baryons [13,14,15] (see also a recent review [16]), being motivated by Ref. [17].

In the present talk, we want briefly explain how the newly-found excited $\Omega_c^0$’s [6] can be classified uniquely within the framework of the pion mean-field approaches: Three of the excited $\Omega_c$’s can be naturally understood as the members of the excited baryon sextet whereas two of them, which have relatively smaller decay widths, should belong to the ground baryon anti-decapentaplet. If this scenario turns out true, then the charged $\Omega_c^*$’s in the invariant-mass $\Xi^+_c K^0$ and $\Xi^0_c K^-$ channels will be observed.

2 Singly heavy baryons as a system of $N_c - 1$ valence quarks in pion mean fields

In the pion mean-field approach, a light baryon in a low-lying representation can be regarded as $N_c$ valence quarks self-consistently bound by the pion mean fields that are produced by the valence quark themselves. The process is nothing but a well-known Hartree approximation from atomic and nuclear physics. On the other hand, a singly heavy baryon consists of the $N_c - 1$ valence quarks while the heavy quark is regarded as a spectator, i.e. a mere static color source in the limit of the infinitely heavy quark mass ($m_Q \to \infty$), as depicted in Fig. 1. Thus,

![Fig. 1. Lowest-lying singly heavy baryons.](image-url)
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In this case, allowed representations must include states with the value of $Y'$ when $N_c = 3$: the antitriplet ($\bar{3}$), the sextet (6), and the anti-decapentaplet ($\bar{15}$) as illustrated in Fig. 2. The isospin $T$ of the ground states with $Y' = (N_c - 1)/3$

![Fig. 2. Allowed representations of the singly heavy baryons](image)

is also constrained by the relation $T + J = K = 0$, where $J$ denotes the soliton spin that must be coupled to $T$ to give the grand spin $K$. The ground-state heavy baryons must have $K = 0$ because all the valence quarks lie in the state $K^P = 0^+$ with parity $P$. By these selection rules, the $\bar{3}$ has the soliton spin 0 whereas the 6 has spin 1. The $\bar{15}$ has both spin 0 and 1. The soliton spin being coupled to the heavy-quark spin 1/2, the singly heavy baryons can be finally constructed as the antitriplet with spin 1/2, the sextet with spin 1/2 and 3/2, that will be split by a hyperfine interaction, and the anti-decapentaplet with 1/2 and 3/2.

While a nucleon or a hyperon is excited by triggering a lowest-lying valence quark to hop into the next excited level with $K^P = 1^-$, the most favorable way of describing an excited singly heavy baryon is to excite a sea quark in the $K^P = 1^-$ level to an unoccupied $K^P = 0^+$ level to fill up, as demonstrated in Fig. 3. Using

![Fig. 3. Excited heavy baryons](image)
the quantization rule $K = J + T$, we can classify the allowed representations for the excited baryons. Since $K = 1$, we first consider the simplest case $T = 0$ that gives $J = 1$, which belongs to the excited baryon anti-triplet. Combining a charm quark with spin 1/2, we find there are two excited antitriplet representations respectively with spin 1/2 and 3/2, which will be split by a certain hyperfine interaction. When $T = 1$, the allowed $J$ of the soliton can be $J = 0, 1, 2$. Being coupled to the charm quark, five different sextet representations appear.

3 Two scenarios for identifying excited $\Omega_c$’s

Very recently, Ref. [8] have scrutinized the spectrum of the excited $\Omega_c$’s reported by the LHCb Collaboration within the framework of the $\chi$QSM. Since five excited $\Omega_c$’s were found, it is very natural to regard them as the members of the excited baryon sextets, since we have exactly the five sextet representations as shown previously. Thus, we first examined how these five sextet representations are split.

Expressing the mass splitting between $J = 0$ and $J = 1$ states as $\Delta_1$ and that between $J = 1$ and $J = 2$ states as $\Delta_2$, we find a relation $\Delta_2 = 2\Delta_1$ within the present approach [8]. This relation is the robust one that will play a role of a touchstone to judge which scenario is more plausible and viable. In addition, one needs to find the hyperfine splittings between the sextets. Assuming that $\Lambda_c^+(2595)$ and $\Xi_c(2790)$ belong to the excited antitriplet with $J^P = 1/2^-$ whereas $\Lambda_c(2625)$ and $\Xi_c(2818)$ are the members of that with $3/2^-$, we can fix the parameter $\kappa'/m_c \approx 30$ MeV for the hyperfine splitting. The hyperfine splitting between the sextet with $1/2^-$ and $3/2^-$ is given by the same $\kappa'/m_c$ as in the antitriplet, but that between the sextet with $3/2^-$ and $5/2^-$ is written by $5\kappa'/3m_c$.

In the first scenario, we assume that the five excited $\Omega_c$’s found by the LHCb belong to each baryon sextet. As mentioned previously, it seems a natural scenario, since there are five representations of the sextet. However, this first scenario leads to the discrepancies that $\kappa'/m_c$ should be at least two times smaller than that determined from the baryon antitriplet and the relation $\Delta_2 = \Delta_1$ is badly broken within this assumption. In addition, the sum rules between the $\Omega_c^*$ masses are also unfavorably violated (see Ref. [8] for details).

Thus, we propose the second scenario in which we assert that three of $\Omega_c^*$’s together with certain bump structures above 3.2 GeV in the LHCb data belong to the five baryon sextet while two of them ($\Omega_c(3050)$ and $\Omega_c(3119)$), which have smaller decay widths, are associated with the anti-decapentaplet. First of all, the relation $\Delta_2 = 2\Delta_1$ is almost perfectly satisfied and the value of the hyperfine splitting is obtained to be $\kappa'/m_c \approx 25$ MeV which is much closer to that determined from the baryon anti-triplet in comparison with the first scenario. Since the $1\bar{5}$ is one of the lowest representations for the singly heavy baryons, we have $J = T = 1$. Being coupled to the heavy-quark spin, there exist two different $1\bar{5}$ representations with 1/2$^+$ and 3/2$^+$, respectively. We assign spin 1/2 to $\Omega_c(3050)$ whereas $\Omega_c(3119)$ is allocated to a spin 3/2 state.
Surprisingly, the hyperfine mass splitting between $\Omega_c$(3050) and $\Omega_c$(3119) is 69 MeV, which is in excellent agreement with the value obtained from the ground-state baryon sextet: $\kappa/m_c = (68.1 \pm 1.1)$ MeV. The results indicate that the second scenario successfully classifies the five excited $\Omega_c$’s observed by the LHCb Collaboration.

Since the $\Omega_c$(3050) and $\Omega_c$(3119) have a rather smaller decay widths than the other $\Omega_c$’s, we have to show that the $\chi$QSM model can explain it. In Ref. [9], the strong decay widths of the ground-state singly heavy baryons and baryon anti-decapentaplet. Since all the dynamical parameters for the axial-vector transitions were already fixed by using the semileptonic decay constants of the SU(3) hyperons [18], one can immediately compute the strong decay widths of the anti-decapentaplet $\Omega_c$’s. In flavor SU(3) symmetry, we were able to reproduce very well the existing experimental data on the strong decay widths of the transition from the ground-state baryon sextet ($6_{1/2}$ and $6_{3/2}$) to the ground-state antitriplet ($3$) [9]. Having shown that the present approach successfully describes the known experimental data on the heavy-baryon strong decays, we continued to compute the strong decays of $\Omega_c$(3050) and $\Omega_c$(3119).

There are three decay modes for $\Omega_c$(3050), i.e. $\Omega_c(1\overline{5}_1,1/2) \rightarrow \Xi_c(30,1/2) + K$, $\Omega_c(1\overline{5}_1,3/2) \rightarrow \Xi_c(30,1/2) \rightarrow \Omega_c(6_1,1/2) + \pi$, and $\Omega_c(1\overline{5}_1,1/2) \rightarrow \Omega_c(6_1,1/2) + \pi$, whereas $\Omega_c$(3119) can decay into four different modes: $\Omega_c(3050)$, i.e. $\Omega_c(1\overline{5}_1,3/2) \rightarrow \Xi_c(30,1/2) + K$, $\Omega_c(1\overline{5}_1,3/2) \rightarrow \Xi_c(30,1/2) \rightarrow \Omega_c(6_1,1/2) + K$, $\Omega_c(1\overline{5}_1,3/2) \rightarrow \Omega_c(6_1,3/2) + \pi$, and $\Omega_c(1\overline{5}_1,3/2) \rightarrow \Omega_c(6_1,3/2) + \pi$. We obtained the total decay widths of $\Omega_c$(3050) and $\Omega_c$(3119) as $\Gamma_{\Omega_c(3050)} = 0.48$ MeV and $\Gamma_{\Omega_c(3119)} = 1.12$ MeV, respectively. Compared to the experimental data $\Gamma_{\Omega_c(3050)} = (0.8 \pm 0.2 \pm 0.1)$ MeV and $\Gamma_{\Omega_c(3119)} = (1.1 \pm 0.8 \pm 0.4)$ MeV, the present results are in very good agreement with the data. Moreover, the smallness of the $\Omega_c$(3050) and $\Omega_c$(3119) decay widths is clearly explained by large cancellation between the leading order and the next-to-leading order corrections in the large $N_c$ expansion. In fact, the widths of the pentaquarks vanish in the nonrelativistic limit of the present model, which is the very same as the case of the light pentaquark $\Theta^+$. The smallness of the decay widths is one of the typical characteristics of a pentaquark states. Results for other members of the $1\overline{5}$, we refer to Refs. [89].

4 Conclusion and outlook

As noted previously, if one classifies the $\Omega_c$(3050) and $\Omega_c$(3119) as the members of the baryon anti-decapentaplet, their isospins should be equal to one. It implies that there must be three $\Omega_c$ in each $1\overline{5}$ representation with different charges. Thus, the $\Omega_c^+$ and $\Omega_c^-$ should exist. In fact, both the $\Omega_c$(3050) and $\Omega_c$(3119) were observed in the invariant mass of the $\Xi_c^+ K^-$ channel. Thus, there is a chance for other isospin members to be found in the charged channels, i.e. $\Xi_c^+ K^0$ or $\Xi_c^0 K^-$ decay channels. Corresponding experiments can be performed by the LHCb and Belle II Collaborations. We anticipate possible findings of the charged $\Omega_c$’s in near future. The strong decays of the heavy baryons and excited $\Omega_c$ are under investigation with flavor SU(3) symmetry breaking taken into account.
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