1/mQ and 1/Nc Expansions for Excited Heavy Baryons with Light Quarks in the Spin-Flavor Symmetric Representation (Postprint)

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Full Text

Preamble

1/mQ and 1/Nc Expansions for Excited Heavy Baryons with Light Quarks in the Spin-Flavor Symmetric Representation

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Abstract

The mass spectrum of the L = 1 orbitally excited heavy baryons with light quarks in the spin-flavor symmetric representation is studied using the 1/Nc expansion method within the framework of heavy quark effective theory. The mixing effect from baryons in the mixed representation is considered. The general pattern of the spectrum is predicted, which will be verified by experiments in the near future. The 1/mQ and SU(3) corrections are also considered, and mass relations for the baryons Λ(∗)c1, Σ(∗)c1, Ξ( )(∗), and Ω(∗)c1 are derived.

1. HQET

A substantial amount of experimental data for orbitally excited heavy baryons has been accumulating [1,2]. Understanding these states will extend our ability to apply QCD. The heavy quark effective theory (HQET) [3] provides a systematic framework for investigating hadrons containing a single heavy quark. However, to obtain detailed predictions, nonperturbative QCD methods must be employed. In this paper, we apply the 1/Nc expansion [4] to the analysis. Within this framework, the masses of L = 1 orbitally excited heavy baryons with light quarks in both spin-flavor symmetric and mixed representations have been analyzed [5]. Using HQET sum rules, the masses of the lowest excited baryon states have also been calculated [6,7]. These states have been studied in other approaches as well, including quark models [8], chiral Lagrangian formalism [9], and the Skyrme model or large Nc limit [10]. In constituent quark models [8], the classification of baryons according to light quark spin-flavor symmetry is taken to be physical.

In the treatment of baryons with light quarks in the spin-flavor symmetric representation in Ref. [5], it was erroneous to consider only one light quark being excited. In fact, it is the heavy quark that is orbitally excited. Note that the orbital excitation of the heavy quark is not suppressed by the heavy quark mass. Rather, it is the light quark pair as a whole—where the two light quarks have zero relative orbital angular momentum—that is excited to L = 1 [6-9]. This paper reconsiders the excited heavy baryons with light quarks in the spin-flavor symmetric representation using the 1/Nc expansion approach within HQET. The results are remarkably simple. Furthermore, we discuss the mixing between the two types of representations via 1/Nc expansion, which is argued to be small. Therefore, our results are both physical and predictive.

Many features of heavy hadrons have been analyzed in HQET. In the heavy quark limit, the heavy quark spin decouples from the strong interaction. The mass of a heavy hadron H is expanded as

$$M_H = m_Q + \bar{\Lambda}_H - \frac{\lambda_1^H}{2m_Q} - \frac{d_H \lambda_2}{2m_Q}$$

where m_Q is the heavy quark mass, the parameter $\bar{\Lambda}_H$ is independent of the heavy quark spin and flavor and describes primarily the contribution of the light degrees of freedom in the baryon. λ_1^H and λ_2^H are the kinetic and chromomagnetic matrix elements, respectively:

$$\lambda_1^H = \langle H(v)|\bar{h}_v (iD)^2 h_v |H(v)\rangle,$$

$$\lambda_2^H = -\langle H(v)|\bar{h}_v \frac{g}{2}\sigma_{\mu\nu} G^{\mu\nu} h_v |H(v)\rangle,$$

with h_v denoting the heavy quark field with velocity v. The quantities $\bar{\Lambda}_H$, λ_1^H, and λ_2^H must be calculated using nonperturbative HQET.

At this stage, we apply the 1/Nc expansion in the analysis. It is one of the most important model-independent methods in nonperturbative QCD. Nonperturbative properties of mesons can be understood from the analysis of planar diagrams, and baryons from the Hartree-Fock picture. For ground state baryons, it has been found that there is a contracted SU(2Nf) light quark spin-flavor symmetry in the large Nc limit [11–14]. This enables a 1/Nc expansion based on spin-flavor structure for baryons, leading to many quantitative predictions and further extensions [15–20].

Before proceeding, two remarks are necessary. First, the aforementioned 1/Nc expansion applies to s- or p-wave states of low spin in the baryon multiplet. States with spin of order Nc/2 are considerably modified by spin-spin and spin-orbit interactions [12]. Second, it is actually Nc − 1, which equals 2 in the real world, that should be treated as a large number because the heavy quark is distinguished. This is an improvement compared to the 1/Nc expansion for excited heavy baryons with light quarks in the mixed representation, where the expansion parameter is Nc − 2 [5].

The quantum numbers describing hadrons are angular momentum J and isospin I. For heavy hadrons, the total angular momentum of the light degrees of freedom J_l becomes a good quantum number in HQET. In the light quark spin-flavor symmetric representation, the light degrees of freedom in H appear as a collection of Nc − 1 light quarks without orbital angular momentum excitation. This picture for the light quarks is essentially the same as that for ground state heavy baryons. The spin-flavor decomposition rule is $I = S_l$ for non-strange baryons, where S_l is the total spin of the light quark system.

Note that the light quark system as a whole has L = 1 orbital angular momentum. In other words, the heavy quark is now orbitally excited to L = 1. In the real world, Nc is fixed to be 3, so there are only two light quarks in a heavy baryon. The spin-flavor structure of these is quite simple: $(I, S_l) = (0, 0)$ and $(1, 1)$. All possible states of excited heavy baryons are listed in Table I. In the table, except for the third state, the other six states form three pairs, each being a doublet under heavy quark spin symmetry.

We adopt the Hartree-Fock picture to study $\bar{\Lambda}_H$ where, in the baryon H, the light quarks are in the spin-flavor symmetric representation. One essential point of the 1/Nc expansion is the Nc counting rules for relevant Feynman diagrams. In the Hartree-Fock picture of baryons, these counting rules require us to include many-body interactions in the analysis, rather than only one- or two-body interactions. However, a large portion of these interactions are spin-flavor irrelevant, meaning this part contributes universally at order $N_c\Lambda_{QCD}$ to all baryons with different spin-flavor structures in Table I. This leads to a 1/Nc expansion based on the light quark spin-flavor structure of baryons, allowing us to obtain mass splittings among baryons in the same light quark spin-flavor representation.

For the purely light quark contribution to $\bar{\Lambda}_H$, the 1/Nc analysis proceeds similarly to that for ground state heavy baryons [12]. There is a light quark spin-flavor symmetry at leading order in the 1/Nc expansion. $\bar{\Lambda}_H$ is trivially $\sim N_c\Lambda_{QCD}$ at this order. Mass splittings due to violation of light quark spin-flavor symmetry begin at order S_l^2/N_c [12]. However, unlike ground state baryons, the orbital angular momentum of the heavy quark formally gives a more dominant contribution to $\bar{\Lambda}_H$ than $O(1/N_c)$. This arises from orbital-light-quark-spin interactions. After summing all relevant many-body interactions, this $O(1)$ contribution is $\mathbf{L}\cdot\mathbf{S}_l f(\mathbf{S}_l^2)$, where f is a general function that can be Taylor expanded.

The mass $\bar{\Lambda}_H$ can be written simply as

$$\bar{\Lambda}_H = N_c\tilde{c}_0 + \tilde{c}_1\mathbf{L}\cdot\mathbf{S}_l + \tilde{c}_2\mathbf{S}_l^2,$$

where coefficients $\tilde{c}_i \sim \Lambda_{QCD}$ $(i = 0, 1, 2)$. There should also be a term proportional to L^2 in the above equation, which gives a constant contribution to $\bar{\Lambda}_H^0$ for a given light quark representation and has therefore been absorbed into the leading term. The term $\mathbf{L}\cdot\mathbf{S}_l$ can be rewritten as $J_l^2 - S_l^2$ with $\mathbf{J}_l$ defined as $\mathbf{J}_l = \mathbf{L} + \mathbf{S}_l$. Therefore,

$$\bar{\Lambda}_H = N_c c_0 + c_1(J_l^2 - S_l^2) + c_2 S_l^2,$$

where coefficients $c_i \sim \Lambda_{QCD}$ need to be determined from experiments.

Numerical results are also given on the right-hand side of Table I. Because the mass formula in Eq. (4) is rather simple, some features of the spectrum can still be discussed. The parameters c_0 and c_2 are naturally expected to be positive. However, c_1 can have either sign.

If $c_1 > 0$, we see that the singlet state $(J, I) = (\frac{1}{2}, 1)$ could be the lowest state. By requiring the first doublet to be the lowest, we must have $c_2 > 2N_c c_1$. The resulting spectrum will be

$$M(\frac{1}{2}, 0, 1, 0) < M(\frac{1}{2}, 1, 0, 1) < M(\frac{3}{2}, 1, 1, 1) < M(\frac{5}{2}, 1, 2, 1)$$

with the quantum numbers denoting J, I, J_l, and S_l, respectively. On the other hand, if $c_1 < 0$, the first doublet represents the lowest states only if $c_2 > -N_c c_1$. In this case, the singlet is the heaviest, and the spectrum is

$$M(\frac{1}{2}, 0, 1, 0) < M(\frac{5}{2}, 1, 2, 1) < M(\frac{3}{2}, 1, 1, 1) < M(\frac{1}{2}, 1, 0, 1).$$

Neither of the above spectrum patterns is consistent with quark model predictions [8]. It should be noted that our analysis neglected the $1/N_c^3$ correction (relative to leading order), which is expected to be insignificant.

The conditions for c_2 are not entirely satisfactory, although they are not unreasonable considering that in the real world N_c is not large. In fact, this unsatisfactory aspect can be avoided if we consider mixing effects from baryons in the mixed representation.

It is necessary to consider mixing between baryons with light quarks in the spin-flavor symmetric and mixed representations. When they share the same quantum numbers (J, I, J_l), there is no physical way to distinguish them. This consideration yields the physical spectrum. Due to light quark spin-flavor symmetry at leading order in the 1/Nc expansion, baryons with the same (J, I, J_l) quantum numbers but in different representations do not mix. Mixing occurs at subleading order. The classification of baryons by spin-flavor symmetry is therefore physical at leading order [21]. For the physical spectrum, mixing results in a deviation from $\bar{\Lambda}_H^0$. Denoting the mixing mass as $\tilde{m}$ which is $O(1)$, the mass matrix for baryons with the same (J, I, J_l) is written as

$$\begin{pmatrix} \bar{\Lambda}_H^0 & \tilde{m} \\ \tilde{m} & \bar{\Lambda}_{H'}^0 \end{pmatrix}$$

where H' is the corresponding baryon in the mixed representation. $\bar{\Lambda}_{H'}^0$ was given in Ref. [5]. The mass difference $\bar{\Lambda}_H^0 - \bar{\Lambda}_{H'}^0$ is $O(1)$. Taking $\tilde{m} < \bar{\Lambda}_{H'}^0 - \bar{\Lambda}_H^0$ for illustration, the physical masses are corrected to be

$$\bar{\Lambda}_H \simeq \bar{\Lambda}_H^0 - \frac{\tilde{m}^2}{\bar{\Lambda}_{H'}^0 - \bar{\Lambda}_H^0},$$

$$\bar{\Lambda}_{H'} \simeq \bar{\Lambda}_{H'}^0 + \frac{\tilde{m}^2}{\bar{\Lambda}_{H'}^0 - \bar{\Lambda}_H^0}.$$

The mixing effect $(\bar{\Lambda}_{H'}^0 - \bar{\Lambda}_H^0)$ is positive. It reduces the predictive power of Eq. (4) for the mass spectrum. The 1/Nc expansion of $\tilde{m}$ is parameterized as

$$\tilde{m} = \tilde{m}_0 + O(1/N_c),$$

where $\tilde{m}_0$ is universal due to light quark spin-flavor symmetry. To $O(1)$ order, the spectrum is given explicitly as follows:

$$\bar{\Lambda}(\frac{1}{2},0,1) = N_c c_0 + 2c_1 - 2c_2 + k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1,$$

$$\bar{\Lambda}(\frac{1}{2},1,0) = N_c c_0 - 2c_1,$$

$$\bar{\Lambda}(\frac{1}{2},1,1) = N_c c_0 - 2c_2 + k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1,$$

$$\bar{\Lambda}(\frac{3}{2},1,2) = N_c c_0 + 4c_1,$$

where k is an $O(1)$ constant remaining after the $\bar{\Lambda}^0_{H'}$ and $\bar{\Lambda}^0_H$ cancellation, $\bar{\Lambda}^0_{H'}$ is parameterized by c_{LS}, $\bar{c}_1$, and $\bar{c}_2$ which are of order Λ_{QCD}, and can be found in Table II of Ref. [5] (where $\bar{c}_1$ and $\bar{c}_2$ were denoted as c_1 and c_2, respectively). Note that the masses of states $(\frac{1}{2},1,0)$ and $(\frac{5}{2},1,2)$ are not affected by mixing because there are no physical states with the same quantum numbers in the mixed representation.

From the above spectrum, we see that $c_1 > 0$. The states $(\frac{5}{2},1,2)$ are always the highest. They are heavier than the other states by at least $4c_1$ when requiring the states $(\frac{1}{2},0,1)$ to be the lowest. If $2c_1 > k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1$, this requirement implies

$$k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1 > 4c_1.$$

In this case, the spectrum pattern is

$$M(\frac{1}{2},0,1) < M(\frac{1}{2},1,0) < M(\frac{3}{2},1,1) < M(\frac{5}{2},1,2).$$

On the other hand, if $2c_1 < k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1$, the requirement is

$$k - c_{LS} - \frac{1}{6}\bar{c}_1 - \frac{1}{4}\bar{c}_2 - 2c_1 > 2c_1,$$

which gives the spectrum

$$M(\frac{1}{2},0,1) < M(\frac{3}{2},1,1) < M(\frac{1}{2},1,0) < M(\frac{5}{2},1,2).$$

Experimentally, the excited charmed baryons $\Lambda_{c1}(\frac{1}{2})$ and $\Lambda_{c1}(\frac{3}{2})$ have been found, corresponding to the $(\frac{1}{2}, 0, 1)$ states. More data are needed to determine the unknown parameters c_i, $\bar{c}_i$, k, and c_{LS}. Future experiments will test the above predicted spectrum, and hopefully one of these mass patterns will be confirmed. This would validate our method if the parameters are in a reasonable range (Λ_{QCD}) while satisfying the relations given above.

For a complete analysis of heavy hadron masses, 1/mQ corrections must be considered. The general expressions for these corrections are given in Eqs. (1) and (2). The quantities λ_1^H and λ_2^H can be analyzed via 1/Nc expansion similarly to $\bar{\Lambda}_H$. In the leading order of 1/Nc, λ_1^H is independent of the light quark structure and scales as unity. Therefore we have the expansion

$$\lambda_1^H = \tilde{c}_0' + \tilde{c}_1' \mathbf{L} \cdot \mathbf{S}_l + c_2'(J_l^2 - S_l^2).$$

Mixing effects also affect λ_1^H. Its 1/Nc expansion shows that the non-vanishing contribution begins at $O(1/N_c)$, and at this order the contribution is constant and can be absorbed into c_0'. The parameters $c_0'/2m_Q$ and $c_1'/2m_Q$ can be absorbed into c_0 and c_1 in Eq. (4), respectively. The inclusion of λ_1^H corrects baryon masses at order $1/m_Q$, which is expected to be insignificant. It does not change the mass pattern given above to order $O(1/m_Q N_c)$.

The degeneracy in the spectrum due to heavy quark spin symmetry is lifted by λ_2^H. According to the definition in Eq. (2), λ_2^H is heavy baryon spin-dependent. It is convenient to extract this dependence explicitly:

$$\lambda_2^H = d_H \lambda_2,$$

where $d_H = 2j_l$ for H with $J = j_l + \frac{1}{2}$, and $d_H = -2j_l - 2$ for H with $J = j_l - \frac{1}{2}$. The newly defined heavy quark hadronic matrix element λ_2 is heavy baryon spin-independent. It is also independent of the light quark structure and scales as unity in the leading order 1/Nc expansion. Like λ_1^H, the 1/Nc expansion for λ_2^H is

$$\lambda_2^H = d_H \left[c_0'' + c_2''(J_l^2 - S_l^2) \right].$$

The mixing effect for λ_2^H is such that the leading non-zero contribution is $O(1/N_c)$, which is constant and therefore can be absorbed into c_0''. The parameters c_i'' should be determined from experimental data. Working to an accuracy of $\Lambda_{QCD}/(m_Q N_c) \sim 10\%$, c_0'' can be fixed from the mass splitting of $\Lambda_{c1}(\frac{3}{2})$ and $\Lambda_{c1}(\frac{1}{2})$:

$$M_{\Lambda_{c1}(\frac{3}{2})} - M_{\Lambda_{c1}(\frac{1}{2})} \simeq \frac{2c_0''}{m_c} \simeq (128 \text{ MeV})^2,$$

by taking $m_c \simeq 1.5$ GeV. Note that c_0'' is positive. The mass splittings of the other degenerate states listed in Table I are predicted to be

$$M(\frac{3}{2},1,2,1) - M(\frac{5}{2},1,2,1) \simeq 55 \text{ MeV},$$

$$M(\frac{1}{2},1,1,1) - M(\frac{3}{2},1,1,1) \simeq 33 \text{ MeV},$$

to the accuracy of $c_0''^2/(m_c N_c)$, which is about 5 MeV. These predictions can be checked against experiments in the near future.

Finally, let us consider excited heavy baryons with light quarks including the strange quark. Very recently, experimental evidence for the charmed-strange analogs of $\Lambda_{c1}(\frac{3}{2})$, the $\Xi_{c1}(\frac{3}{2})$ particles, has been found [2]. The above framework can be easily extended to include charmed-strange baryons by treating strangeness as a perturbation to light quark flavor symmetry. The relevant baryon mass is then expressed as

$$M_H = m_Q + N_c c_0 + c_1(J_l^2 - S_l^2) + \text{mixing} + c_3(-s) + O\left(\frac{s^2}{N_c}\right) + O\left(\frac{\Lambda_{QCD}}{m_Q}\right) + O\left(\frac{\Lambda_{QCD}}{m_Q N_c}\right),$$

where s is the heavy baryon strangeness number which can be 0, -1, or -2. The parameter c_3 represents the leading order SU(3) correction to $\bar{\Lambda}_H$ given in Eq. (4). It is fixed by the mass difference between $\Xi_{c1}(\frac{3}{2})$ and $\Lambda_{c1}(\frac{3}{2})$:

$$c_3 \simeq 190 \text{ MeV}.$$

The mass of $\Xi_{c1}(\frac{1}{2})$ is then predicted to be 190 MeV higher than $\Lambda_{c1}(\frac{1}{2})$:

$$M_{\Xi_{c1}(\frac{1}{2})} = M_{\Lambda_{c1}(\frac{1}{2})} + M_{\Xi_{c1}(\frac{3}{2})} - M_{\Lambda_{c1}(\frac{3}{2})} \simeq 2784 \text{ MeV}.$$

Note that this prediction is subject only to a small uncertainty of about $c_3^2/(m_c N_c) \sim 10$ MeV. Future experiments may find that the particles $\Sigma_{c1}^{(*)}$, which are the lowest charmed L = 1 states with isospin 1, correspond to the state pair $[\frac{1}{2},1,1,1]$ in Table I. Their strange analogs $\Xi_{c1}'^{(*)}$ and $\Omega_{c1}^{(*)}$ can then be predicted rather precisely from similar relations:

$$M_{\Xi'_{c1}(\frac{3}{2})} - M_{\Sigma_{c1}(\frac{3}{2})} = M_{\Xi'_{c1}(\frac{1}{2})} - M_{\Sigma_{c1}(\frac{1}{2})} + O\left(\frac{s}{m_c N_c}\right),$$

$$M_{\Omega_{c1}(\frac{3}{2})} - M_{\Sigma_{c1}(\frac{3}{2})} = M_{\Omega_{c1}(\frac{1}{2})} - M_{\Sigma_{c1}(\frac{1}{2})} + O\left(\frac{s}{m_c N_c}\right).$$

To the accuracy of $s^2/N_c \sim 30\%$,

$$M_{\Omega^{(*)}} - M_{\Sigma^{(*)}} \simeq (190 \pm 70)\ \text{MeV}.$$

In summary, we have applied the 1/Nc expansion method to study the mass spectrum of L = 1 orbitally excited heavy baryons with light quarks in the spin-flavor symmetric representation within the framework of HQET. The analysis is much simpler than that for heavy baryons with light quarks in the mixed representation in Ref. [5]. This simplicity is a unique feature of this case, arising from the perspective that the light quark system is in its ground state while the heavy quark is orbitally excited. However, mixing effects due to baryon states in the mixed representation correct the spectrum pattern at subleading order in the 1/Nc expansion. This effect is important for obtaining a realistic spectrum at this order. The general pattern of the baryon spectrum has been presented, which will be verified by experiments in the near future. Both 1/mQ and SU(3) corrections have been considered, and certain mass relations for the baryons $\Lambda_{c1}^{(*)}$, $\Sigma_{c1}^{(*)}$, $\Xi^{(')(*)}$, and $\Omega_{c1}^{(*)}$ have been derived. The same analysis can be applied to bottom baryons.

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TABLES

Table I. Excited heavy baryon states of the symmetric representation of $N_c - 1$ light quarks. The masses are those without considering mixing.

(J, I)	(J_l, S_l)	Mass
$(\frac{1}{2}, 0)$	$(1, 0)$	$N_c c_0 + 2c_1$
$(\frac{3}{2}, 0)$	$(1, 0)$	$N_c c_0 + 2c_1$
$(\frac{1}{2}, 1)$	$(0, 1)$	$N_c c_0 - 2c_1 + 2c_2$
$(\frac{1}{2}, 1)$	$(1, 1)$	$N_c c_0 + 2c_2$
$(\frac{3}{2}, 1)$	$(1, 1)$	$N_c c_0 + 2c_2$
$(\frac{3}{2}, 1)$	$(2, 1)$	$N_c c_0 + 4c_1 + 2c_2$
$(\frac{5}{2}, 1)$	$(2, 1)$	$N_c c_0 + 4c_1 + 2c_2$

Note: Figure translations are in progress. See original paper for figures.