Excited heavy baryon spectrum in large Nc heavy quark effective theory (postprint)

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Abstract

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Full Text

Preamble

Excited heavy baryon spectrum in large Nc heavy quark effective theory

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Abstract

We analyze the masses of L = 1 excited heavy baryons using heavy quark and large Nc expansions. In the heavy quark limit, the mass is parameterized by $\bar{\Lambda}$ and further expanded in terms of spin-flavor breaking operators to zeroth order in $1/N_c$. The expansion coefficients will be determined by future experimental data on excited baryons.

I. Introduction

A wealth of data on orbitally excited heavy baryons will become available in the near future, and understanding their properties will extend our ability to apply

QCD in the heavy quark sector [?]. In this paper, we study their masses using heavy quark and large Nc expansions. Heavy quark effective theory (HQET) [?] provides a powerful framework for analyzing hadrons containing a single heavy quark, and has been successfully applied to many features of heavy mesons and baryons.

In the $m_Q \to \infty$ limit, where m_Q is the heavy quark mass, the heavy quark spin decouples from the strong interaction and the hadron respects heavy quark spin-flavor symmetry (HQS). At order $1/m_Q$, this symmetry is broken. The masses of excited heavy baryons can be expressed as

$$M = m_Q + \bar{\Lambda} + \mathcal{O}(1/m_Q)$$

where the parameter $\bar{\Lambda}$ is independent of heavy quark spin and flavor, and encodes the contributions from the light degrees of freedom in the baryon. The $1/m_Q$ corrections are parameterized by coefficients c_1 and c_2 given by

$$c_1 = -\langle H_Q(v)|\bar{Q}_v (iD)^2 Q_v|H_Q(v)\rangle$$

$$c_2 = -Z_Q\langle H_Q(v)|\bar{Q}_v g G_{\mu\nu}\sigma^{\mu\nu} Q_v|H_Q(v)\rangle$$

where $H_Q(v)$ is the hadron state with velocity v and Z_Q is the renormalization factor. The parameters $\bar{\Lambda}$, c_1, and c_2 must be determined by nonperturbative methods.

At this stage, we employ the large N_c expansion to analyze $\bar{\Lambda}$. Large N_c QCD has been developed to study the nonperturbative properties of hadrons [?]. In the large N_c limit, baryons can be treated as bound states of an infinite number of valence quarks. Witten described this system using a Hartree-Fock picture and derived N_c counting rules for meson-baryon scattering amplitudes [?]. Dashen, Jenkins, and Manohar (DJM) discovered a light quark spin-flavor symmetry for the ground state baryon sector in the large N_c limit by deriving consistency conditions (first obtained by Gervais and Sakita [?]) for pion-baryon coupling constants based on N_c counting rules [?]. This symmetry was later understood in the Hartree-Fock picture [?, ?], where s-wave states of low spin in the baryon multiplet are spin-independent, while states with spin of order $N_c/2$ are significantly modified by spin-spin and spin-orbit interactions.

Orbitally excited baryons have also been investigated [?]. Regarding baryon masses, Ref. [?] derived consistency conditions for the strong couplings of excited baryons to pions analogous to those in Refs. [?, ?], while Goity [?] analyzed excited light baryons in the Hartree-Fock picture. Further developments were presented in Ref. [?]. We adopt the Hartree-Fock picture to study $\bar{\Lambda}$.

One concern with our approach is the validity of the large N_c approximation. In practice, we treat $N_c - 2$ (which equals 1 in the real world) as a large number because the heavy quark and the excited light quark are distinguished. For excited light baryons, the large parameter is $N_c - 1$. The large N_c approach has been shown to describe the spectrum well [?], which motivates us to generalize the method to excited heavy baryons, particularly given the limited understanding of nonperturbative HQET.

This paper is organized as follows. In Sec. II, we classify excited heavy baryons according to the large N_c spin-flavor structure of the light degrees of freedom. In Sec. III, we introduce the leading spin-flavor symmetry breaking operators involving spin-orbit, spin-isospin, and spin-orbit-isospin correlations, compute their matrix elements in the basis established in Sec. II, and present numerical results. We summarize our findings in Sec. IV.

II. Classification of the Excited Heavy Baryons

Hadrons are characterized by the quantum numbers angular momentum J and isospin I. For heavy hadrons, HQS makes the total angular momentum of the light degrees of freedom, J_ℓ, a good quantum number, leading to degenerate pairs of states related by HQS. In baryons, the light degrees of freedom consist of $N_c - 1$ light quarks, with one being orbitally excited.

Experimentally, several excited charmed baryons have been discovered [?], with the lowest-lying pair being $\Lambda_{c1}(\frac{1}{2})^+$ and $\Lambda_{c1}(\frac{3}{2})^+$, both having isospin $I = 0$. In the constituent quark picture, the total spin of the light quarks S_ℓ is also zero [?], which guides us to focus on the symmetric representation of the $N_c - 1$ light quarks.

Figure 1: see original paper shows the Young tableaux for the symmetric representation of $N_c - 1$ quarks. The spin-flavor decomposition is identical to that of ground state heavy baryons [?], following the rule $I = S_\ell$ for non-strange baryons. Importantly, one of the light quarks is orbitally excited with $\ell = 1$. In the real world where $N_c = 3$, heavy baryons contain only two light quarks, one of which is excited. The spin-flavor structure of these two light quarks is simple: $(I, S_\ell) = (0, 0)$ and $(1, 1)$ for $N_f = 2$. All possible excited heavy baryon states are listed in Table I. The first two entries correspond to $\Lambda_{c1}(\frac{1}{2})^+$ and $\Lambda_{c1}(\frac{3}{2})^+$. For comparison, we also show the mixed representation of the $N_c - 1$ light quarks in Fig. 1(b) and Table II.

It is convenient to introduce K-spin defined by $\vec{K} = \vec{I} + \vec{S}_\ell$, which is a good quantum number whenever light quark spin-flavor symmetry holds (as it does for baryons in the large N_c limit). The symmetric representation corresponds to $K = 0$, while the mixed representation corresponds to $K = 1$. Tables I and II reveal that, unlike excited light baryons [?], no mixing occurs between states belonging to different K representations for excited heavy baryons. With only two light quarks, it is impossible to have the same (I, S_ℓ) pair with different K.

III. Mass Splittings

Using the classification from the previous section, we now study the spectrum of excited heavy baryons, particularly the mass splittings among them, using the large N_c method in the heavy quark limit. If we strictly take the large N_c limit, at leading order ($N_c\Lambda_{\text{QCD}}$) we obtain a trivial result: all finitely excited heavy baryons have the same mass as the ground state heavy baryon. This occurs because both excited and ground state baryons contain an infinite number of unexcited light quarks, making the contribution of the finitely excited quarks negligible. Such a conclusion is not practically useful since, in reality, there is only one quark in the core. The key insight of recent approaches [?] is that mass splittings arising from spin-flavor structure can be analyzed using large N_c methods.

Let us examine the large N_c method in more detail. An essential ingredient is the N_c counting rules for relevant Feynman diagrams. In the Hartree-Fock picture of baryons, these rules require including many-body interactions rather than just one- or two-body interactions. However, most of these interactions are spin-flavor independent, contributing universally at order $N_c\Lambda_{\text{QCD}}$ to all baryons regardless of spin-flavor structure. The many-body Hamiltonians related to spin-flavor structure that involve orbital angular momentum L give contributions of order $\mathcal{O}(1)$. It is reasonable to assume these can be treated perturbatively.

We employ the same operators used in Ref. [?] to analyze $\bar{\Lambda}$:

$$H_{LS} \propto \hat{a}^\dagger \vec{L} \cdot \vec{\sigma} \hat{a}$$

$$H_T \propto \hat{a}^\dagger L_i \otimes \tau^a \hat{a} G^{ia}$$

$$H_i \propto \hat{a}^\dagger \{L_i, L_j\} \otimes \sigma_i \otimes \tau^a \hat{a} G^{ja}$$

Here H_{LS} is a one-body Hamiltonian, while the others are two-body Hamiltonians. The G^{ia} are generators of the spin-flavor symmetry group $SU(4)$, given by $G^{ia} = \hat{a}^\dagger \sigma_i \otimes \tau^a \hat{a}$, where σ_i and τ^a are spin and isospin matrices, respectively. This structure yields coherent addition over the $N_c - 2$ core quarks. The first G^{ia} in H_T acts on the excited quark, while the other G^{ia} operators act on the $N_c - 2$ unexcited light quarks (the core). All operators must be understood as acting on the light degrees of freedom. Higher-order many-body Hamiltonians with additional factors of G^{ia} can be reduced to those in Eq. (3) [?].

The contributions to baryon masses from these Hamiltonians are obtained by calculating baryonic matrix elements. The matrix elements between light quark states that specify excited heavy baryon states are given by expressions analogous to those in Ref. [?]:

$$\langle I_c = \tfrac{1}{2}; II_3; S'_\ell S'_{\ell 3}|H_T|I_c = \tfrac{1}{2}; II_3; S_\ell S_{\ell 3}\rangle = 2c_T \delta_{S'_\ell,S_\ell}\delta_{S'_{\ell 3},S_{\ell 3}}\delta_{m,m'}(-1)^{1-S_\ell-I}$$

$$\langle I_c = \tfrac{1}{2}; II_3; \ell=1, S'_\ell, J_\ell J_{\ell 3}|H_{LS}|I_c = \tfrac{1}{2}; II_3; \ell=1, S_\ell, J_\ell J_{\ell 3}\rangle = c_{LS}(-1)^{S_\ell - S'_\ell}\sqrt{(2S_\ell+1)(2S'_\ell+1)}(2j+1)\{j(j+$$

$$\langle I_c = \tfrac{1}{2}; II_3; \ell=1, S'_\ell, J_\ell J_{\ell 3}|H_1|I_c = \tfrac{1}{2}; II_3; \ell=1, S_\ell, J_\ell J_{\ell 3}\rangle = 6c_1(-1)^{I-J_\ell+S_\ell-S'_\ell-1}\sqrt{(2S_\ell+1)(2S'_\ell+1)}$$

$$\langle I_c = \tfrac{1}{2}; II_3; \ell=1, S'_\ell, J_\ell J_{\ell 3}|H_2|I_c = \tfrac{1}{2}; II_3; \ell=1, S_\ell, J_\ell J_{\ell 3}\rangle = 3c_2(-1)^{1+J_\ell+I+S'_\ell+2S_\ell}\sqrt{(2S_\ell+1)(2S'_\ell+1)}$$

where I_c is the isospin of the core quarks. In the real world ($N_c = 3$), there is only one quark in the core ($N_c - 2 = 1$), so I_c is always equal to $\frac{1}{2}$.

With these matrix elements, we can express the excited heavy baryon mass up to zeroth order in $1/m_Q$ and $1/N_c$ as:

$$M = m_Q + \bar{\Lambda}, \quad \bar{\Lambda} = \Lambda_0 + \langle H_{LS}\rangle + \langle H_T\rangle + \sum_{i=1}^{2}\langle H_i\rangle$$

where c_{LS}, c_T, and c_i are coefficients to be determined experimentally, and Λ_0 is the leading contribution to $\bar{\Lambda}$ that preserves spin-flavor symmetry.

Numerical results are presented on the right-hand side of Tables I and II. Current experimental data give $\Lambda_{c1}^+(J=\frac{1}{2}) = 2593.9 \pm 0.8$ MeV and $\Lambda_{c1}^+(J=\frac{3}{2}) = 2626.6 \pm 0.8$ MeV [?]. Taking $m_c = 1.5$ GeV and $\Lambda_0 = N_c\Lambda_{\rm QCD} = 1.0$ GeV yields $-\frac{1}{6}c_T \simeq 0.1$ GeV. Additional experimental data are needed to determine the remaining coefficients. In the study of light excited baryons [?], $\langle H_T\rangle$ gave the same value for all states in a given tower and could be absorbed into the leading contribution. In our case, as shown in Table I, $\langle H_T\rangle$ takes different values within the symmetric representation, while in the mixed representation it is constant across the tower. Compared to the mixed representation, mass splittings of symmetric states due to H_T and H_i are opposite in sign and three times smaller except for $(J_\ell, S_\ell) = (1,0)$. This difference arises from isospin effects. In the future, these coefficients can be fitted once the three masses with quantum numbers $(J_\ell, S_\ell) = (0,1)$, $(1,1)$, and $(2,1)$ in the symmetric representation are measured. The validity of our method can be checked by whether the resulting values of c_{LS}, c_1, and c_2 fall in reasonable ranges, as we found for c_T.

IV. Summary

We have analyzed the mass splittings of orbitally excited heavy baryons using $1/m_Q$ and $1/N_c$ expansions. In the heavy quark limit, the heavy quark spin decouples and the baryon is described by its light degrees of freedom. At zeroth order in $1/N_c$, we have calculated the effects of light quark spin-flavor symmetry breaking from one one-body operator and three two-body operators, parameterized by several coefficients that require more data on excited charmed baryons to be determined.

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Figure Captions

Fig. 1 Young’ s tableaux for (a) symmetric and (b) mixed representation of $N_c - 1$ light quarks.

Table Captions

Table I . Excited heavy baryon states of the symmetric representation of $N_c - 1$ light quarks.

Table II . Excited heavy baryon states of the mixed representation of $N_c - 1$ light quarks.

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