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Degeneracy of doubly heavy baryons from heavy quark symmetry

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ABSTRACT

The spectroscopy of the doubly heavy baryons including different heavy quarks is studied based on the heavy quark symmetry of QCD. We point out that, when the two heavy quarks are in S-wave, these baryons with a certain spin j_l of the light cloud can be classified into two sets: a heavy quark singlet with total spin of $j = j_l$ and a heavy quark multiplet with $j = (j_l + 1), j_l, \ldots |j_l - 1|$, all the baryons in these two sets have the same mass and, the baryons with the same quantum numbers in these two sets do not mix with each other. We finally point out that the strong decay of the first excited baryon with light spin $j_l = 1/2$ to the ground state and one-pion is determined by the mass splitting through the generalized Goldberger–Treiman relation.

The physics of heavy hadrons has become a hot subject in particle and nuclear physics because of the observations of a large amount of such states during the last decade in scientific facilities. With the collection of more data and updating of facilities, more and more states must be observed in the present and upcoming facilities such as BESIII, LHCb and Belle II. The observation of the hidden charm pentaquark state at LHCb [1] strongly indicates that it is the time to study baryons with two heavy quarks, the doubly heavy baryons (DHBs).

The DHB is an immediate prediction from the quark model. Even though the DHBs have been extensively discussed theoretically using several models in the literature [2–19], there are controversial results in the experimental hunting [20–27]. It is useful to provide some more theoretical guidance by different models for the future experimental search.

In this work, we will focus on the spectroscopy of the DHBs with different heavy quarks based on the heavy quark symmetry (see, e.g. Ref. [28] for a review). In a DHB with different heavy quarks, say Q and Q', the two heavy quarks in the S-wave can form a spin singlet and a spin triplet. For simplicity, we write the spin singlet and the spin triplet as $\bar{\Phi}^{(QQ')}$ and $\bar{\Phi}_\mu^{(QQ')}$, respectively, with both $\bar{\Phi}^{(QQ')}$ and $\bar{\Phi}_\mu^{(QQ')}$ being the color anti-triplet. Due to the spin-flavor symmetry in the heavy quark limit, $\bar{\Phi}^{(QQ')}$ and $\bar{\Phi}_\mu^{(QQ')}$ have the same mass, i.e.,

$$M(\bar{\Phi}^{(QQ')}) = M(\bar{\Phi}_\mu^{(QQ')}) \,. \tag{1}$$

The interaction between the heavy diquarks, $\Phi^{(QQ')}$ and $\bar{\Phi}_\mu^{(QQ')}$, and gluons can be easily written down by considering that both $\Phi^{(QQ')}$ and $\bar{\Phi}_\mu^{(QQ')}$ are the color anti-triplets. By taking the heavy quark limit, the effective Lagrangian for the diquarks is expressed as

$$\mathcal{L}_{\rm eff}^{\Phi} = \bar{\Phi}^{(QQ')} i\, v_\nu (\partial^\nu + igG^\nu)\bar{\Phi}^{(QQ')\dagger} + \bar{\Phi}^{(QQ')\mu} i\, v_\nu (\partial^\nu + igG^\nu)\bar{\Phi}_\mu^{(QQ')\dagger} \,, \tag{2}$$

where v_ν is the velocity of the diquarks, G^ν is the gluon field and g is the gauge coupling constant of QCD. Effective Lagrangian (2) implies that the two diquarks have the same interaction with the gluon which combines them to a light degree of freedom ("Brown muck") to form two types of heavy baryons.

Now, we are in the position to study the mass relation of the DHBs with quark content $QQ'q$ where q stands for a light quark constituent.

We first consider the DHBs in the ground state. In such a case, we schematically write the DHBs as $D_{\mathbf{Q}} \equiv \bar{\Phi}^{(QQ')}q$ and $D_{\mathbf{Q}}^\mu \equiv \bar{\Phi}^{(QQ')\mu}q$, where q symbolically denotes the Brown muck in the ground state which carries the spin-parity $j_l^P = \frac{1}{2}^+$. Since the scalar diquark $\bar{\Phi}^{(QQ')}$ carries spin zero, the spin-parity of the $D_{\mathbf{Q}}$ is $j^P = \frac{1}{2}^+$. Therefore $D_{\mathbf{Q}}$ is a heavy quark singlet. On the other hand, since the axial-vector diquark $\bar{\Phi}_\mu^{(QQ')}$ carries spin one, the spin-parity of the $D_{\mathbf{Q}}^\mu$ is either $j^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$ which forms a heavy quark doublet. With respect to Eq. (2), we see that the singlet $D_{\mathbf{Q}}$ and doublet $D_{\mathbf{Q}}^\mu$ have the same mass, i.e.,

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Table 1
Pattern of mass degeneracy of the ground states and the first excited states. Notations are explained in the main text.

J_Q	l	j_l^P	j^P	Mass relation
0	0	$\frac{1}{2}^+$	$\frac{1}{2}^+$	degenerate
1	0	$\frac{1}{2}^+$	$(\frac{3}{2}^+, \frac{1}{2}^+)$	
0	1	$\frac{1}{2}^-$	$\frac{1}{2}^-$	degenerate
1	1	$\frac{1}{2}^-$	$(\frac{3}{2}^-, \frac{1}{2}^-)$	
0	1	$\frac{3}{2}^-$	$\frac{3}{2}^-$	degenerate
1	1	$\frac{3}{2}^-$	$(\frac{5}{2}^-, \frac{3}{2}^-, \frac{1}{2}^-)$	

$$M(D_{\mathbf{Q}}) = M(D^\mu_{\mathbf{Q}}) \, . \tag{3}$$

Furthermore, the states with the same quantum number, explicitly those with $j^P = \frac{1}{2}^+$, in $D_{\mathbf{Q}}$ and $D^\mu_{\mathbf{Q}}$ cannot mix due to the difficulty of the heavy quark spin flipping. Then, we arrive at the conclusion that, in the heavy quark limit, the ground states of the DHBs with different heavy quarks form a heavy quark singlet and a heavy quark doublet which are classified by the total spin of the heavy diquark included in them and the DHBs in these two sets have the same mass.

Next, we consider DHBs with the first orbital excitation with relative angular momentum between the light quark and heavy diquark source $l = 1$. In such a case, the quantum numbers of the Brown muck could be $j_l^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$. Combining the $j_l^P = \frac{1}{2}^-$ light component with the heavy component $\bar{\Phi}^{(QQ')}$ and $\bar{\Phi}^{(QQ')}_\mu$ one can form a heavy quark singlet $N_{\mathbf{Q}}$ with $j^P = \frac{1}{2}^-$ and a heavy quark doublet $N^\mu_{\mathbf{Q}}$ with $j^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. In analogy to the discussion made to the ground states, the baryons in the heavy quark singlet $N_{\mathbf{Q}}$ and those in the heavy quark triplet $N^\mu_{\mathbf{Q}}$ have the same mass. When we combine the $j_l^P = \frac{3}{2}^-$ component to the heavy diquarks one gets a heavy quark singlet $T^\mu_{\mathbf{Q}}$ with quantum numbers $j^P = \frac{3}{2}^-$ and a heavy quark triplet $T'^\mu_{\mathbf{Q}}$ with quantum numbers $j^P = \frac{5}{2}^-, \frac{3}{2}^-, \frac{1}{2}^-$. Again, from the effective Lagrangian (2) we conclude that all the baryons in the heavy quark singlet $T^\mu_{\mathbf{Q}}$ and heavy quark triplet $T'^\mu_{\mathbf{Q}}$ have the same mass and the two baryons with quantum numbers $j^P = \frac{3}{2}^-$ decouple from each other.

From the above discussion, we arrive at our conclusion that, *for DHBs with total light spin-parity j_l^P, they can be classified into two sets: a heavy quark singlet with quantum numbers $j^P = j_l^P$ and a heavy quark multiplet with quantum numbers $j^P = (j_l + 1)^P, \cdots, (|j_l - 1|)^P$. These baryons have degenerate masses and the two baryons with quantum numbers $j^P = j_l^P$ in these two sets do not mix to each other due to heavy quark spin conservation in the heavy quark limit*. Examples of the ground states and first excited states are summarized in Table 1.

After the above discussion on the pattern of the mass degeneracy, we turn to the strong decays of the DHBs. Because the heavy quarks in a DHB have large masses, the light quark in the DHB sees the heavy diquark as a local source of gluon, which makes the picture of the DHB analogues to the heavy–light meson [4]. Then, to analyze the strong decays of the DHBs with $j_l^P = \frac{1}{2}^-$, we use the chiral partner structure applied in the heavy–light meson sector [29,30]. There, the heavy-quark doublet including $j^P = 0^-$ and $j^P = 1^-$ heavy–light mesons is regarded as the chiral partner of the doublet including $j^P = 0^+$ and $j^P = 1^+$ heavy–light mesons. The coupling strengths of interactions between two doublets are determined from the mass differences through generalized Goldberger–Treiman relations, which are in good agreement with experiments [31–33]. The difference here is that, in the heavy–light meson sector the heavy component is a heavy quark but in the DHB sector the heavy component is a heavy diquark made of two heavy quarks. But this difference does not affect the chiral structure which is controlled by the light quark degree of freedom in a hadron. In addition, since it takes much more energy to excite the heavy diquark constituent in a DHB, we regard the excited DHB as those with the light quark excitation in it. Similar to the heavy–light meson sector, we regard the DHBs with the Brown muck of $j_l^P = \frac{1}{2}^-$, i.e., the heavy quark singlet $N_{\mathbf{Q}}$ and heavy quark doublet $N^\mu_{\mathbf{Q}}$, as the chiral partners to the ground states, i.e., $D_{\mathbf{Q}}$ and $D^\mu_{\mathbf{Q}}$, respectively. Note that, as in the heavy–light meson sector [34], the extension of the present discussion to the excited states is straightforward.

To accommodate the chiral dynamics in the DHB sector, along Ref. [19], we introduce the left- and right-handed DHB fields $D^{(\mu)}_{\mathbf{Q};L,R}$ which, at the quark level, are schematically written as $D^{(\mu)}_{\mathbf{Q};L,R} \sim \bar{\Phi}^{(\mu)} q_{L,R}$. Under chiral transformation, they transform as

$$D^{(\mu)}_{\mathbf{Q};L,R} \to g_{L,R} D^{(\mu)}_{\mathbf{Q};L,R} , \tag{4}$$

where $g_{L,R} \in SU(2)_{L,R}$ when we consider only the up and down quarks in the DHBs. In terms of $D^{(\mu)}_{\mathbf{Q}}$ and $N^{(\mu)}_{\mathbf{Q}}$, one can write

$$\begin{aligned} D^{(\mu)}_{\mathbf{Q};L} &= \frac{1}{\sqrt{2}} \left(D^{(\mu)}_{\mathbf{Q}} - i N^{(\mu)}_{\mathbf{Q}} \right), \\ D^{(\mu)}_{\mathbf{Q};R} &= \frac{1}{\sqrt{2}} \left(D^{(\mu)}_{\mathbf{Q}} + i N^{(\mu)}_{\mathbf{Q}} \right), \end{aligned} \tag{5}$$

which transform as $D^{(\mu)}_{\mathbf{Q};L,R} \leftrightarrow \gamma_0 D_{\mathbf{Q};(\mu);R,L}$ under parity transformation and satisfy $\not{v} D^{(\mu)}_{\mathbf{Q};L,R} = D^{(\mu)}_{\mathbf{Q};L,R}$ and $v_\mu D^\mu_{\mathbf{Q};L,R} = 0$ for preserving the heavy quark symmetry and keeping the transversality. Further, for later convenience, we write the DHB doublets $D^{(\mu)}_{\mathbf{Q}}$ and $N^{(\mu)}_{\mathbf{Q}}$ in terms of the physical states. For $D_{\mathbf{Q}}$ and $N_{\mathbf{Q}}$ we have

$$D_{\mathbf{Q}} = \frac{1+\not{v}}{2} \Psi'_{QQ'}, \quad N_{\mathbf{Q}} = \frac{1+\not{v}}{2} \Psi'^*_{QQ'}, \tag{6}$$

where $\Psi'_{QQ'}$ and $\Psi'^*_{QQ'}$ are Dirac spinors for the DHBs with $j^P = \frac{1}{2}^+$ and $\frac{1}{2}^-$, respectively. Note that the parity transformations of $\Psi'_{QQ'}$ and $\Psi'^*_{QQ'}$ are given as

$$\mathrm{P}: \ \ \Psi'_{QQ'} \to \gamma_0 \Psi'_{QQ'}, \quad \Psi'^*_{QQ'} \to -\gamma_0 \Psi'^*_{QQ'} . \tag{7}$$

The expressions of $D^\mu_{\mathbf{Q}}$ and $N^\mu_{\mathbf{Q}}$ in terms of physical states and their transformation are given in Ref. [19]. We will not repeat them here. In terms of the naming scheme in PDG, $\Psi^{(\prime)}_{QQ'}$ stands for $\Xi^{(\prime)}_{bc}$ and $\Omega^{(\prime)}_{bc}$ for the DHB including un-flavored quark and strange quark, respectively.

Following the procedure used in Ref. [19] one can easily construct an effective Lagrangian of $D^{(\mu)}_{\mathbf{Q}}$ and $N^{(\mu)}_{\mathbf{Q}}$ first in the chiral basis in a chiral invariant way and then rewrite it in terms of $D^{(\mu)}_{\mathbf{Q}}$ and $N^{(\mu)}_{\mathbf{Q}}$. There is no coupling between the heavy-quark doublet and heavy quark singlet because of the heavy quark spin conservation. The chiral effective Lagrangian is simply a duplicate of the one given in Ref. [19] which is written in the chiral basis as

$$\begin{aligned} \mathcal{L}_{\mathrm{B}} = {} & \bar{D}^{(\mu)}_{\mathbf{Q};L} i v \cdot \partial D_{\mathbf{Q};(\mu);L} + \bar{D}^{(\mu)}_{\mathbf{Q};R} i v \cdot \partial D_{\mathbf{Q};(\mu);R} \\ & - \Delta \left(\bar{D}^{(\mu)}_{\mathbf{Q};L} D_{\mathbf{Q};(\mu);L} + \bar{D}^{(\mu)}_{\mathbf{Q};R} D_{\mathbf{Q};(\mu);R} \right) \\ & - \frac{1}{2} g_\pi \left(\bar{D}^{(\mu)}_{\mathbf{Q};L} M D_{\mathbf{Q};(\mu);R} + \bar{D}^{(\mu)}_{\mathbf{Q};R} M^\dagger D_{\mathbf{Q};(\mu);L} \right) \end{aligned}$$