D-Wave Heavy Baryons from QCD Sum Rules

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We study the D -wave heavy baryons using the method of QCD sum rules in the framework of heavy quark effective theory. Our results suggest that the $\Lambda_c(2860)$, $\Lambda_c(2880)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ complete two D -wave $SU(3)$ flavor $\bar{\mathbf{3}}_F$ charmed baryon doublets of $J^P = 3/2^+$ and $5/2^+$.

Keywords: Excited heavy baryons; QCD sum rule; heavy quark effective theory.

1. Introduction

In the past years important experimental progresses have been made in the field of heavy baryons¹. All the $1S$ charmed baryons have been well established, and the

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$1P$ states $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Xi_c(2790)$ and $\Xi_c(2815)$ have also been well observed and complete two $SU(3)$ flavor $\mathbf{\bar{3}}_F$ multiplets of $J^P = 1/2^-$ and $3/2^-$. Besides them, there still exist many higher states, and various phenomenological methods and models were applied to investigate them. We refer to reviews^{2,3,4,5} for their recent progress.

In this paper we shall concentrate on the $\Lambda_c(2860)$, $\Lambda_c(2880)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ ^{1,6}. To study them, we shall use the method of QCD sum rules^{7,8} in the framework of heavy quark effective theory^{9,10,11}. This method has also been applied to study the S - and P -wave heavy baryons^{12,13,14}.

2. QCD Sum Rule Analyses

In Refs. 15, 16 we have systematically constructed all the D -wave heavy baryon interpolating fields. Here we briefly explain our notations: $J_{j,P,F,j_l,s_l,\rho-\lambda}^{\alpha_1\cdots\alpha_{j-1/2}}$ denotes the D -wave heavy baryon field belonging to the baryon multiplet $[F, j_l, s_l, \rho - \lambda]$, where j , P , and F are its total angular momentum, parity and $SU(3)$ flavor representation ($\mathbf{\bar{3}}_F$ or $\mathbf{6}_F$), respectively; j_l and s_l are the total angular momentum and spin angular momentum of its light components, respectively. There are three types: $\rho\rho$ -type ($l_\rho = 2$ and $l_\lambda = 0$), $\lambda\lambda$ -type ($l_\rho = 0$ and $l_\lambda = 2$) and $\rho\lambda$ -type ($l_\rho = 1$ and $l_\lambda = 1$), where l_ρ is the orbital angular momentum between the two light quarks, and l_λ is the orbital angular momentum between the heavy quark and the two-light-quark system.

We summarize all the possible configurations of the D -wave ($L = 2$) charmed baryons in Fig. 1, where **A** and **S** denote the structure to be antisymmetric and symmetric, respectively. The explicit forms of $J_{j,P,F,j_l,s_l,\rho-\lambda}^{\alpha_1\cdots\alpha_{j-1/2}}$ have been given in Eqs. (2–19) of Ref. 15. Here we use the current $J_{3/2,+, \Lambda_c, 2, 0, \lambda\lambda}^\alpha$ as an example:

$$J_{3/2,+, \Lambda_c, 2, 0, \lambda\lambda}^\alpha(x) = \epsilon_{abc} \left([\mathcal{D}_{\mu_1}^t \mathcal{D}_{\mu_2}^t u^{aT}(x)] \mathbb{C} \gamma_5 d^b(x) + \right. \\ \left. 2[\mathcal{D}_{\mu_1}^t u^{aT}(x)] \mathbb{C} \gamma_5 [\mathcal{D}_{\mu_2}^t d^b(x)] + u^{aT}(x) \mathbb{C} \gamma_5 [\mathcal{D}_{\mu_1}^t \mathcal{D}_{\mu_2}^t d^b(x)] \right) \\ \times \left(\frac{1}{2} g_t^{\mu_1\alpha} g_t^{\mu_2\mu_4} + \frac{1}{2} g_t^{\mu_2\alpha} g_t^{\mu_1\mu_4} - \frac{1}{3} g_t^{\mu_1\mu_2} g_t^{\mu_4\alpha} \right) \times \gamma_{\mu_4}^t \gamma_5 h_v^c(x). \quad (1)$$

We use it to perform QCD sum rule analyses. We refer to Refs. 12–17 for details, but simply list here the equation to evaluate the mass of the heavy baryon belonging to the multiplet $[F, j_l, s_l, \rho - \lambda]$:

$$m_{j,P,F,j_l,s_l,\rho-\lambda} = m_Q + \bar{\Lambda}_{F,j_l,s_l,\rho-\lambda} + \delta m_{j,P,F,j_l,s_l,\rho-\lambda}, \quad (2)$$

where $\bar{\Lambda}_{F,j_l,s_l,\rho-\lambda} = \bar{\Lambda}_{|j_l-1/2|,P,F,j_l,s_l,\rho-\lambda} = \bar{\Lambda}_{j_l+1/2,P,F,j_l,s_l,\rho-\lambda}$ is the sum rule result obtained at the leading order, and $\delta m_{j,P,F,j_l,s_l,\rho-\lambda}$ is the sum rule result obtained at the $\mathcal{O}(1/m_Q)$ order:

$$\delta m_{j,P,F,j_l,s_l,\rho-\lambda} = -\frac{1}{4m_Q} (K_{F,j_l,s_l,\rho-\lambda} + d_M C_{mag} \Sigma_{F,j_l,s_l,\rho-\lambda}). \quad (3)$$

$[\rho\rho] \quad l_\rho = 2 \text{ (S)}, \quad l_\lambda = 0, \quad \bar{\mathbf{3}}_C \text{ (A)}$

$$\begin{aligned}
 \bar{\mathbf{3}}_F \text{ (A): } L=2 \otimes s_l=0 \text{ (A)} & \longrightarrow j_l=2: \Lambda_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\rho\rho\text{-a}) [\bar{\mathbf{3}}_F, 2, 0, \rho\rho] \\
 \mathbf{6}_F \text{ (S): } L=2 \otimes s_l=1 \text{ (S)} & \begin{cases} j_l=1: \Sigma_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) \quad \Xi_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) \quad \Omega_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) & (\rho\rho\text{-b}) [\mathbf{6}_F, 1, 1, \rho\rho] \\ j_l=2: \Sigma_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Omega_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\rho\rho\text{-c}) [\mathbf{6}_F, 2, 1, \rho\rho] \\ j_l=3: \Sigma_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) \quad \Xi_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) \quad \Omega_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) & (\rho\rho\text{-d}) [\mathbf{6}_F, 3, 1, \rho\rho] \end{cases}
 \end{aligned}$$

$[\lambda\lambda] \quad l_\rho = 0 \text{ (S)}, \quad l_\lambda = 2, \quad \bar{\mathbf{3}}_C \text{ (A)}$

$$\begin{aligned}
 \bar{\mathbf{3}}_F \text{ (A): } L=2 \otimes s_l=0 \text{ (A)} & \longrightarrow j_l=2: \Lambda_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\lambda\lambda\text{-a}) [\bar{\mathbf{3}}_F, 2, 0, \lambda\lambda] \\
 \mathbf{6}_F \text{ (S): } L=2 \otimes s_l=1 \text{ (S)} & \begin{cases} j_l=1: \Sigma_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) \quad \Xi_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) \quad \Omega_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) & (\lambda\lambda\text{-b}) [\mathbf{6}_F, 1, 1, \lambda\lambda] \\ j_l=2: \Sigma_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Omega_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\lambda\lambda\text{-c}) [\mathbf{6}_F, 2, 1, \lambda\lambda] \\ j_l=3: \Sigma_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) \quad \Xi_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) \quad \Omega_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) & (\lambda\lambda\text{-d}) [\mathbf{6}_F, 3, 1, \lambda\lambda] \end{cases}
 \end{aligned}$$

$[\rho\lambda] \quad l_\rho = 1 \text{ (A)}, \quad l_\lambda = 1, \quad \bar{\mathbf{3}}_C \text{ (A)}$

$$\begin{aligned}
 \mathbf{6}_F \text{ (S): } L=2 \otimes s_l=0 \text{ (A)} & \longrightarrow j_l=2: \Sigma_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Omega_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\rho\lambda\text{-a}) [\mathbf{6}_F, 2, 0, \rho\lambda] \\
 \bar{\mathbf{3}}_F \text{ (A): } L=2 \otimes s_l=1 \text{ (S)} & \begin{cases} j_l=1: \Lambda_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) \quad \Xi_{c1} \left(\frac{1}{2}^+, \frac{3}{2}^+ \right) & (\rho\lambda\text{-b}) [\bar{\mathbf{3}}_F, 1, 1, \rho\lambda] \\ j_l=2: \Lambda_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) \quad \Xi_{c2} \left(\frac{3}{2}^+, \frac{5}{2}^+ \right) & (\rho\lambda\text{-c}) [\bar{\mathbf{3}}_F, 2, 1, \rho\lambda] \\ j_l=3: \Lambda_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) \quad \Xi_{c3} \left(\frac{5}{2}^+, \frac{7}{2}^+ \right) & (\rho\lambda\text{-d}) [\bar{\mathbf{3}}_F, 3, 1, \rho\lambda] \end{cases}
 \end{aligned}$$

$L=0/1$: we do not study these two cases in this paper.

Fig. 1. D-wave charmed baryons.

Still use the current $J_{3/2,+, \Lambda_c, 2, 0, \lambda\lambda}^\alpha$ as an example. We use it to perform QCD sum rule analyses and calculate $\bar{\Lambda}_{\Lambda_c, 2, 0, \lambda\lambda}$, $K_{\Lambda_c, 2, 0, \lambda\lambda}$ and $\Sigma_{\Lambda_c, 2, 0, \lambda\lambda}$, from which we obtain the following numerical results for the baryon multiplet $[\Lambda_c(\bar{\mathbf{3}}_F), 2, 0, \lambda\lambda]$:

$$\begin{aligned}
 m_{\Lambda_c(3/2^+)} &= 2.81_{-0.18}^{+0.33} \text{ GeV}, \\
 m_{\Lambda_c(5/2^+)} &= 2.84_{-0.20}^{+0.37} \text{ GeV}, \\
 m_{\Lambda_c(5/2^+)} - m_{\Lambda_c(3/2^+)} &= 28_{-24}^{+45} \text{ MeV},
 \end{aligned} \tag{4}$$

Similarly, we obtain the following numerical results for the baryon multiplet $[\Xi_c(\bar{\mathbf{3}}_F), 2, 0, \lambda\lambda]$:

$$\begin{aligned}
 m_{\Xi_c(3/2^+)} &= 3.04_{-0.15}^{+0.15} \text{ GeV}, \\
 m_{\Xi_c(5/2^+)} &= 3.05_{-0.16}^{+0.15} \text{ GeV}, \\
 m_{\Xi_c(5/2^+)} - m_{\Xi_c(3/2^+)} &= 15_{-13}^{+16} \text{ MeV}.
 \end{aligned} \tag{5}$$

The above values are consistent with the experimental masses of the $\Lambda_c(2860)$, $\Lambda_c(2880)$, $\Xi_c(3055)$, and $\Xi_c(3080)^{1,6}$.

3. Summary and Discussions

In this paper we have studied the D -wave charmed baryons using the method of QCD sum rules within the heavy quark effective theory. We have calculated their masses up to the order $\mathcal{O}(1/m_Q)$ with large theoretical uncertainty, and we have also calculated their mass splittings within the same doublet with much less theoretical uncertainty.

Our results suggest that the $\Lambda_c(2860)$, $\Lambda_c(2880)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ complete two D -wave $SU(3)$ flavor $\bar{\mathbf{3}}_F$ charmed baryon doublets $[\bar{\mathbf{3}}_F, 2, 0, \lambda\lambda]$ of $J^P = 3/2^+$ and $5/2^+$. We propose to further investigate their decay properties in order to study the structure of heavy baryons in detail.

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