Puzzle of the Λc spectrum (postprint)

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Abstract

There is a puzzle in the +c family, i.e., one member with JP = 3/2+ is missing in a L = 2 multiplet which the heavy quark effective theory predicts, and JP' s of c(2765)+ and c(2940)+ are unknown. Using a light diquark picture to calculate baryon masses, we study possible assignments of two c' s with unknown JP and the missing +c with 3/2+ for L = 2, and we find the most probable possibility that the peak corresponding to c(2880)+ actually includes a missing member with spin 3/2+ for L = 2 and that quantum numbers of c(2765)+ and c(2940)+ are 2S (1/2+) and 2P(1/2−), respectively.

Full Text

Puzzle of the Λc Spectrum

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There is a puzzle in the Λc family: one member with $J^P = 3/2^+$ is missing in an $L = 2$ multiplet that heavy quark effective theory predicts, and the J^P

values of $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$ are unknown. Using a light diquark picture to calculate baryon masses, we study possible assignments of the two Λ_c states with unknown J^P and the missing c with $3/2^+$ for $L = 2$, and we find the most probable scenario: the peak corresponding to $\Lambda_c(2880)^+$ actually includes a missing member with spin $3/2^+$ for $L = 2$, and the quantum numbers of $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$ are $2S(1/2^+)$ and $2P(1/2^-)$, respectively.

Introduction

In our previous paper [**?**], we pointed out that careful observation of the experimental spectra of heavy-light mesons reveals that heavy-light mesons with the same angular momentum L are almost degenerate, and that mass differences within a heavy quark spin doublet and between doublets with the same L are very small compared with the mass gap between different multiplets with different L, which is nearly equal to $\Lambda_{\text{QCD}} \sim 300$ MeV. In the Conclusions and Discussion of Ref.~[**?**], we also suggested that Λ_c^+ baryons may have properties similar to heavy-light mesons. While there have been papers pursuing similar ideas for light and vector mesons by Afonin and collaborators [**?**, **?**], we do not discuss them in this work.

According to the PDG [**?**], six Λ_c^+ baryons have been observed experimentally: $\Lambda_c(2286)^+$, $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$ (or $\Sigma_c(2765)^+$), $\Lambda_c(2880)^+$, and $\Lambda_c(2940)^+$. Among these, the following heavy quark spin multiplets are identified: $\Lambda_c(2286)$ with $J^P = 1/2^+$ for $L = 0$; $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ with $1/2^+$ and $3/2^+$ for $L = 1$, respectively; and $\Lambda_c(2880)^+$ with $5/2^+$ for $L = 2$. One member is missing in the spin multiplet for $L = 2$ that has spin $3/2^+$. Apart from this missing particle, mass differences within the same multiplet (i.e., with the same L) are very small, and gaps between the average masses of spin multiplets are all ~ 300 MeV, which obeys the rule proposed in Ref.~[**?**]. Despite these successful assignments, a puzzle remains in the Λ_c^+ baryons: where is the missing member for $L = 2$, and what are the quantum numbers J^P for $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$? If we regard $\Lambda_c(2940)^+$ as the missing member of $L = 2$, then this state must have spin-parity $3/2^+$, which contradicts the common understanding that a state with smaller spin 3/2 appears lower in mass than a state with larger spin 5/2. In addition, the strong and radiative decays of $\Lambda_c(2940)$ in a D^*N molecular scenario have been analyzed in Refs.~[**?**, **?**], which argue against spin 3/2.

There is a pioneering work [**?**] that calculates baryon masses by directly extending the method of Godfrey and Isgur [**?**]. However, since this method is complicated, in this article we regard a baryon as a heavy quark-light diquark system $(Q\{qq\})$ as in Ref.~[**?**] and calculate its mass. We show that the above observation on Λ_c holds, predict J^P and spin assignments of $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$, and propose a solution to the puzzle of where the missing member for $L = 2$ is located.

We adopt the method provided in Ref.~[**?**] to calculate baryon masses, whose prescription is as follows: (1) First we calculate diquark masses assuming the relativized quark model proposed by Godfrey and Isgur (GI) [**?**]. (2) Next, having calculated the diquark mass and regarding two light quarks as $3^* \in 3 \times 3$, we again apply the GI model to a heavy quark-light diquark system to obtain the baryon mass.

This calculation method places very tight conditions on parameters, making it very difficult to reproduce physical masses as one might imagine. Hence, we also refer to baryon mass values where diquark masses are treated as parameters to fit experimental data [**?**], and to values given in Refs.~[**?**, **?**, **?**].

Relativized Quark Model and Diquark Masses

To calculate baryon masses, we adopt interactions proposed by the relativized GI model, whose Hamiltonian between quark and antiquark can be expressed as $\tilde{H} = H_0 + \tilde{V}(\mathbf{p}, \mathbf{r})$, where $H_0 = (p^2 + m_1^2)^{1/2} + (p^2 + m_2^2)^{1/2}$ and $\tilde{V}(p, r) = \tilde{H}_{\mathrm{conf}} + \tilde{H}_{\mathrm{cont}} + \tilde{H}_{\mathrm{ten}} + \tilde{H}_{\mathrm{so}}$. Here $\tilde{H}_{\mathrm{conf}}$ includes the spin-independent linear confinement and Coulomb-like interaction. $\tilde{H}_{\mathrm{cont}}$, $\tilde{H}_{\mathrm{ten}}$, and $\tilde{H}_{\mathrm{so}}$ are the color contact, color tensor interactions, and spin-orbit term, respectively. Subindices 1 and 2 denote quark (3_c) and antiquark (3_c^*), respectively. The symbol "$\sim$" on top of the operator $\tilde{H}$ means that we operate the relativized procedure on H, by which relativistic effects are taken into account. The explicit forms of those interactions and the details of the relativization procedure can be found in Refs.~[**?**, **?**] for mesons and baryons, respectively.

To solve Eq.~(1), we need parameter values which are given in Table I provided by Refs.~[**?**, **?**]. Here C_{qq} is taken to be the same as $C_{q\bar{q}}$ in Ref.~[**?**] up to the factor, an inner product $\langle \mathbf{F}_1 \cdot \mathbf{F}_2 \rangle$, with $V_{\mathrm{string}}(\mathbf{r}) = C_{qq}$ (or $C_{q\bar{q}}$) $+ br$. $\tilde{V}$ includes Gell-Mann matrices whose expectation values, $\langle \mathbf{F}_1 \cdot \mathbf{F}_2 \rangle$, are $4/3$ for $q\bar{q}$ and $-2/3$ for a diquark qq. In Table I, "GI" means parameters taken from Ref.~[**?**] and "CI" from Ref.~[**?**], which we adopt in this work to calculate diquark masses as well as heavy quark-diquark (i.e., charmed baryon) masses. In this work, $C_{q\bar{q}}$ is used for $C_{Q\mathrm{di}}$ where Q is a heavy quark and "di" denotes a diquark. The word "same" in the CI column in Table I means the same value as a GI parameter.

[TABLE I]

The calculated diquark masses using both parameter sets of GI and CI are listed in Table II. Although Ref.~[**?**] includes three-body interactions, we neglect them to simplify the calculation.

[TABLE II]

Baryon Masses

After obtaining diquark masses from Table II, we calculate baryon masses using Eq.~(1) with both parameter sets of GI and CI. Although the mass values with the CI parameter set are better than those of GI, we list both results in Table

III as "Prediction (CI/GI)" together with experimental data and other results from Refs.~[**?**, **?**, **?**, **?**]. Among these results, Refs.~[**?**, **?**] use the heavy quark-diquark picture, and Ref.~[**?**] uses the semi-relativistic quark potential model, which should be compared with our results. Since Ref.~[**?**] treats diquark masses as parameters, they obtain a better fit with experimental data than ours. Our self-consistent calculation of the Λ_c baryon masses gives rather higher values compared to other models. Even though our calculated value of 2930 MeV is very close to $\Lambda_c(2940)$, it is natural to consider that our values 2930 and 2919 MeV should form a multiplet for $L = 2$. In this case, we find that the mass difference between members of an $L = 2$ multiplet is within ~ 10 MeV, including other models. Accordingly, we can see a similar tendency for all the models:

1. $\Lambda_c(2765)^+$ is identified as a $|2S, 1/2^+\rangle$ state.
2. $\Lambda_c(2940)^+$ is identified as a $|2P, 1/2^-\rangle$ state.
3. The observed peak of the $\Lambda_c(2880)^+$ assigned as $|1D, 5/2^+\rangle$ actually includes a missing state $|1D, 3/2^+\rangle$ because their predicted masses listed in Table III are so close to each other (within ~ 10 MeV) that they could not be distinguished experimentally.

Items 2 and 3 have already been pointed out in Ref.~[**?**]. As for Item 3, the experimental errors of the mass and width for $\Lambda_c(2880)^+$ are so small—2881.50 ± 0.35 and 5.8 ± 1.1 given in Refs.~[**?**, **?**, **?**], respectively—that one cannot imagine a missing particle hidden in the same peak as $\Lambda_c(2880)^+$. However, there are theoretical uncertainties as one can see from Table III. References~[**?**, **?**] give the same mass values for $|1D, 5/2^+\rangle$ and $|1D, 3/2^+\rangle$, and Refs.~[**?**, **?**] including ours give masses within ~ 10 MeV, so that considering theoretical errors, both states are most probably in one peak or it is very difficult to separate the two states from the peak at 2880 MeV.

[TABLE III]

Conclusions and Discussion

After many XYZ particles have been discovered, attention has focused on explaining their nature—whether they are molecular states, tetraquark states, or just kinematical effects [**?**, **?**, **?**]. Now that most XYZ particles are settling, researchers are directing their energy toward studying heavy baryons, cases where one, two, or three quarks are heavy. Attacking this problem is somewhat harder compared to XYZ particles because baryons consist of three quarks and it is very difficult to solve a three-body problem. A diquark picture makes it easier to calculate both mass spectra and decay behaviors with the help of the $^3P_0$ model as in Ref.~[**?**]. See also Ref.~[**?**] for how to apply the method proposed in [**?**] to baryons.

Starting from the simple observation that many heavy-light mesons have degenerate masses within a heavy quark spin multiplet, we extended this idea to baryons. The first example was the Λ_c baryons. However, there is a puzzle in this spectrum: a missing member in an $L = 2$ heavy-quark spin multiplet.

In this article, we have studied the Λ_c^+ spectrum. To do so, we calculated baryon masses using a heavy quark-diquark picture for baryons and compared them with other theoretical and experimental values. To treat two light quarks as a diquark, we attempted to be self-consistent: we first calculated diquark masses using the GI model with the CI parameter set, and using those diquark masses, we computed baryon masses. After examining the obtained values together with previous theoretical results, we concluded that $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$ are identified as $|2S, 1/2^+\rangle$ and $|2P, 1/2^-\rangle$ states, respectively, and that a missing member of the $L = 2$ heavy-quark spin multiplet is hidden in the peak around $\Lambda_c(2880)^+$.

Because our prediction for the missing member of the $L = 2$ heavy quark multiplet depends on experimental accuracy, future careful measurements of the Λ_c^+ spectrum by LHCb and the forthcoming Belle II are awaited to test our prediction.

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