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Study of heavy-light hadrons within a flux tube model*

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Abstract: A classic mass loaded flux tube model and the diquark picture are employed to explore both mesons and baryons. The spectrum of Λ_c^+ baryons and D_s mesons is systematically obtained. The spin-orbit interaction in D_s was simplified as an $\vec{L}\cdot\vec{S}$ coupling. The spin-orbit interaction in Λ_c was simplified as a $\vec{J}_l\cdot\vec{J}_c$ coupling. The predicted masses are consistent with the latest experiments.

Key words: diquark, spin-orbit interaction, heavy-light hadrons, flux tube model

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1 Introduction

In recent years, a series of charm open hadrons have been observed [1]. Since both the heavy quark symmetry and the light quark chiral symmetry apply in heavy-light hadrons, these have attracted great interest [2–31]. As is well known, the study of hadron spectroscopy is an important way to reveal the properties of quark dynamics. It is also an important way to detect the relation between the quark models and QCD.

The classic flux tube model (mass loaded flux tube model) [3] was first explored 20 years ago. Light mesons and baryons were systematically explored in this model by Selem and Wilczek [4] with the spin-orbit interaction being ignored. Recently, D, D_s and Λ_c have been systematically studied with the spin-orbit interaction taken into account [5–7]. In this paper, the classic flux tube model and our results are briefly introduced.

1.1 Diquark and baryons

In general, a diquark is a "correlated" two quark system. It cannot exist in isolation because of the color confinement, but it might exist in combination with other quark(s) to form a bound state.

A baryon consists of three quarks. This system has complex dynamics. In the constituent quark potential model, the Jacobi coordinates are usually employed to study this three-body system. On the other hand, a baryon, being thought of as a diquark paired with a quark, is also a two-body system. In terms of the diquark, Λ_c^+ baryons have the same picture and dynamics as D_s mesons.

The idea of the diquark was first mentioned by Gell-Mann in 1964 [32]. Since then, the diquark picture has been employed in many models [33–36]. A diquark has sometimes been thought of as a point particle [34].

From dynamics, the wave function of a diquark is always assumed to be antisymmetric. The color part and the spatial part of a diquark are assumed to be antisymmetric and symmetric, respectively [4]. Therefore, $(|\text{flavor}\rangle \times |\text{spin}\rangle)_{\text{diquark}}$ is symmetric. A vector diquark (spin symmetric, 3_s) is always flavor symmetric (6_f) and a scalar diquark (1_s) is always flavor antisymmetric ($\bar{3}_f$).

Phenomenological analysis [36] argued that the vector diquark (qq′) ("bad" diquark) has a greater mass than the singlet diquark [qq′] ("good" diquark). In the diquark picture, it is reasonable to think that there is a "good" diquark in Λ_c^+ (I=0). In Σ_c (I=1), there is very possibly a "bad" diquark.

1.2 Mass loaded flux tube model

So far, people cannot give an accurate spectrum prediction for the bound states based on QCD except for the lattice QCD theory. Instead, many models

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have been employed in an attempt to dynamically understand hadrons. Heavy-light hadrons have been systematically studied in the MIT bag model [2, 8], the relativized quark model [9–11], the heavy quark symmetry theory [12], the relativistic quark model [13], the chiral quark model [14, 15], the coupled channels models [16–18], the lattice theory [19], the constituent quark model, which has both the heavy quark symmetry and the light quark chiral symmetry [20–22], and the flux tube model [3, 5, 7, 23] et al.

The flux tube [3, 5, 7, 23] or string-like model is a simple but effective phenomenological approach. In this model, the QCD confining force between the quark and antiquark or diquark is approximated by a string or a flux tube with some constant tension. That is to say, the flux tube is responsible for the color confinement. The flux tube or string carries both angular momentum and energy [3]. If there exists a diquark in the baryons, the baryons have similar structure and dynamics as the mesons.

As stated in Ref. [4], the energy of a two-body system

$$E = m_1\gamma_1 + m_2\gamma_2 + \frac{T}{\omega}\int_0^{\omega r_1}\frac{1}{\sqrt{1-u^2}}\mathrm{d}u + \frac{T}{\omega}\int_0^{\omega r_2}\frac{1}{\sqrt{1-u^2}}\mathrm{d}u, \tag{1}$$

where ω, r_i and γ_i are parameters in the model.

Similarly, the angular momentum of the system

$$L = m_1\omega r_1^2\gamma_1 + m_2\omega r_2^2\gamma_2 + \frac{T}{\omega^2}\int_0^{\omega r_1}\frac{u^2}{\sqrt{1-u^2}}\mathrm{d}u + \frac{T}{\omega^2}\int_0^{\omega r_2}\frac{u^2}{\sqrt{1-u^2}}\mathrm{d}u. \tag{2}$$

After some algebra and deduction, a formula for the heavy-light system is obtained as follows [4],

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}}\kappa L^{-\frac{1}{4}} m^{\frac{3}{2}}, \tag{3}$$

where M is the heavy quark mass, m is the light antiquark or diquark mass,

$$T = \frac{\sigma}{2\pi},$$

and

$$\kappa \equiv \frac{2}{3}\frac{\pi^{\frac{1}{2}}}{\sigma^{\frac{1}{4}}}.$$

In Eq. (3), the spin-orbit interactions are ignored. However, the spin-orbit interactions contribute largely to the spectra of D, D_s mesons [7] and Λ_c baryons [5]. A simple but reasonable way to include the contribution of spin-orbit interaction is to simplify the interaction as an $\vec{L}\cdot\vec{S}$ coupling [7] or a $\vec{J}_l\cdot\vec{J}_c$ coupling [5].

Accordingly, we got the formula [7]

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}}\kappa L^{-\frac{1}{4}} m^{\frac{3}{2}} + a\vec{L}\cdot\vec{S} \tag{4}$$

for D_s mesons, and the formula [5]

$$E = M + \sqrt{\frac{\sigma L}{2}} + 2^{\frac{1}{4}}\kappa L^{\frac{-1}{4}} m^{\frac{3}{2}} + a\vec{J}_l\cdot\vec{J}_c \tag{5}$$

for Λ_c baryons.

2 Spectrum

In recent years, some new highly excited charmed baryons and mesons have been observed. Though the heavy-light hadrons have been systematically explored in different models, there appears to be some confusion. Some observed states seem to have much lower masses than those predicted by theories, though the lower masses have been explained in some models. In this paper, we make a systematic interpretation of them in the semi-classic mass loaded flux tube model.

2.1 Λ_c^+

A Λ_c baryon ($I=0$) consists of two u, d quarks and one c quark. Therefore, the u and d quark is assumed in [ud] (good diquark) configuration. The good diquark and the c quark are assumed to locate at the ends of the flux tube in Λ_c.

$\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$ (or $\Sigma_c(2765)$), $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are listed in the 2008 review by the PDG [1]. Only the quantum numbers J^P of $\Lambda_c(2880)^+$ have been measured; the J^P of all other states are assigned according to the theoretical predictions.

The spin-parity of $\Lambda_c(2593)^+$ and $\Lambda_c(2625)^+$ was assumed to be

$$J^P = \frac{1}{2}^- \text{ and } J^P = \frac{3}{2}^-,$$

respectively, in Ref. [24]. They form a doublet Λ_{c1}^+

$$\left(\frac{1}{2}^-, \frac{3}{2}^-\right).$$

In Ref. [4], the spin-parity of some Λ_c baryons was assumed, where the spin-orbit forces were ignored. In that work, the fitted parameters are M_c=1.6 GeV, $m_{[ud]} = 0.18$ GeV, and $\sigma = 0.97$ GeV^2 [4]. The mass of the diquark [ud] seems smaller. In fact, the dynamics of the diquark in hadrons are not clear, so the diquark may have different mass in different models.

In Ref. [5], we performed an analysis on Λ_c baryons in the semi-classic mass loaded flux tube model. Our fitted parameters are $m_c = 1.390$ GeV, $m_{qq} = 0.521$ GeV, $\sigma = 0.999$ GeV^2 and $a = 40$ MeV.

The masses of the c quark and the diquark are comparable with most theoretical assignments. Our study indicates that the diquark is a good approximation for Λ_c baryons and the dynamics of Λ_c baryons are well described by the mass loaded flux tube. Our results are shown in Fig. 1. The details of the analysis and the conclusions were presented in Ref. [5].

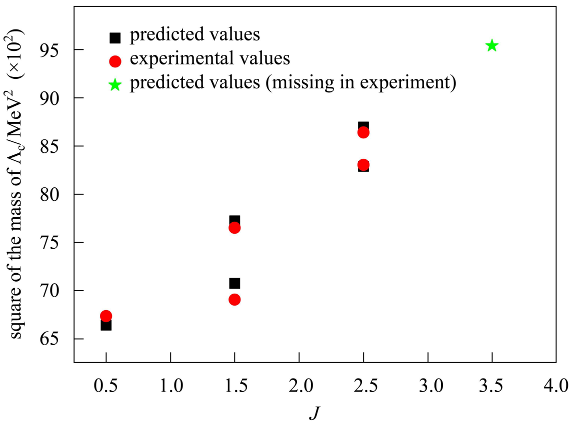

Fig. 1. The total angular momentum of Λ_c (J).

In the following, some words about $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$ are emphasized.

(1) $\Lambda_c(2765)^+$. It is a broad state ($\Gamma \approx 50$ MeV), which was first seen in $\Lambda_c^+\pi^+\pi^-$ by CLEO [37]. In PDG2008 [1], this state is also denoted $\Sigma_c(2765)^+$. In the relativized quark model [38], a $J^P = \frac{1}{2}^+$ Λ_c state with mass $\approx$ 2775 MeV was predicted, accordingly, $\Lambda_c(2765)^+$ was interpreted as the first positive-parity excitation of Λ_c in Ref. [39]. This state was assigned the radial excited 2 $\frac{1}{2}^+$ in Ref. [40] and $J^P = \frac{5}{2}^-$ in Ref. [41], respectively, in the relativistic quark model. In our analysis, a $J^P = \frac{3}{2}^+$ Λ_c with mass 2772 MeV was predicted. Therefore, we suggested the J^P assignment of $\Lambda_c(2765)^+$ be $\frac{3}{2}^+$. We noted that the previously predicted $\frac{1}{2}^+$ $\Lambda_c(2775)$ cannot exist in the mass loaded flux tube model.

(2) $\Lambda_c(2940)^+$. This state was first observed in D^0P decay mode by BABAR [42] and confirmed by Belle in the $\Sigma_c^{0++}\pi^{+-}$ [43] channel. Its J^P is still unknown. The $\frac{5}{2}^-$ or $\frac{3}{2}^+$ assignment to this Λ_c^+ was predicted in the quark potential model [44]. There exists another controversial interpretation in Ref. [45]. In our analysis, $\Lambda_c(2940)^+$ has $J^P = \frac{5}{2}^-$. As a by-product, a $J^P = \frac{7}{2}^-$ charmed baryon $\Lambda_c(3076)^+$ was predicted.

2.2 D_s

A D_s meson is a typical heavy-light system. Heavy quark symmetry holds in D_s, so the quark dynamics in the meson are determined only by the light degrees of freedom. In Ref. [4], though the heavy-light system was not analyzed, a formula for the heavy-light system was given with the spin-orbit interactions being ignored. In Refs. [6, 7], the formula was extended to take into account the spin-orbit interactions. There are usually two kinds of naming schemes for the D_s mesons. One is the nonrelativistic scheme $^{2S+1}L_J$; another is the HQET scheme j^P. For the reason stated in Ref. [7], the nonrelativistic scheme is employed by us. Our fitted parameters are $m_c = 1.600$ GeV, $m_s = 0.288$ GeV, $\sigma = 1.100$ GeV^2 and $a = 38$ MeV [7]. Our results are shown in Fig. 2.

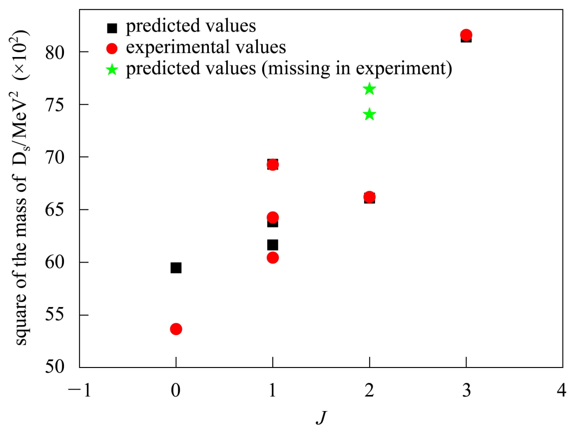

Fig. 2. The total angular momentum of D_s (J).

As is well known, $D_{s0}^*(2317)^\pm$ [46] and $D_{s1}(2460)^\pm$ [47] are popularly assumed to be the 0^+ and the 1^+ D_s, respectively, though there are controversial interpretations [22, 48, 49]. In this paper, we give a brief interpretation of those lately observed D_s states[1)] .

(1) $D_{sJ}(2632)^+$. $D_{sJ}(2632)^+$ is a surprisingly narrow charmed strange meson, which was first reported by SELEX [50] with Γ <17 MeV. $D_{sJ}(2632)^+$ was once suggested as a four-quark state or a conventional 1^- (2^3S_1) $c\bar{s}$ [15, 51]. However, $D_{sJ}(2632)^+$ has not been observed by BABAR, FOCUS or Belle. It seems that this state does not exist. In the semi-classic flux tube model, a 1^- $\frac{3}{2}^-$ (or 1^3D_1) D_s with mass $\approx$ 2.6 GeV is predicted [6]. In the $^3P_0$ model [52], the decay $D_{s1}(1^3D_1) \to D_0K$ is predicted to have width $\Gamma = 3.73$ MeV. In our opinion, if $D_{sJ}(2632)^+$ exists, it is possibly the 1^- 1^3D_1.

1) $D_{sJ}(3040)$ observed lately by BABAR was interpreted in Ref. [6]

(2) $D_{s1}(2700)^{\pm}$. This state was first reported by Belle in $B^+ \to \bar{D}^0 D_{s1} \to \bar{D}^0 D^0 K^+$ with $M = 2715 \pm 11^{+11}_{-14}$ and $\Gamma \approx 115$ MeV. A X(2690) was also reported by BABAR [53], but the significance of the signal was not stated. $D^{\star}_{s1}(2710)^{\pm}$ was recently observed by BABAR [54] with $\Gamma = 149 \pm 7$ MeV in $e^+ + e^- \to D^{\star}_{s1}(2710)^{\pm}X \to D^{\star}KX$. These three experiments give approximately equal mass and decay width, which indicates that they may be the same state. $D_{s1}(2700)^{\pm}$ was interpreted as $1^-(1^3D_1)$, which has a lower mass and a broader width in Ref. [55]. In Refs. [56, 57], it was interpreted as $1^-(2^3S_1)$ D_s (first radial excitation of $D^{\star}_s(2112)^{\pm}$). Considering the fact that its branching ratio [3] is comparable with theoretical predications, the $1^-(2^3S_1)$ assignment is preferred.

(3) $D_{sJ}(2860)$. This state was first reported in $D_{sJ}(2860) \to D^0K^+$, $D^+K^0_s$ with $\Gamma = 48 \pm 7(\text{stat}) \pm 10(\text{syst})$ MeV and branching fraction ratio

$$\frac{\mathcal{B}(D^{*}_{sJ}(2860)^+ \to D^{*}K)}{\mathcal{B}(D^{*}_{sJ}(2860)^+ \to DK)} = 1.10 \pm 0.15_{\text{stat}} \pm 0.19_{\text{syst}},$$

but it has not been confirmed by Belle. It was once supposed to have natural spin-parity, $J^P=0^+, 1^-, \ldots$, but the 0^+ possibility is ruled out by the observation of $D_{sJ}(2860) \to D^{\star}K$ [54]. This state was interpreted as $3^-(1^3D_3)$ in Refs. [55, 58].

In the semi-classical flux tube model, $D_{sJ}(2860)$ is the excellent candidate of $3^-(1^3D_3)$ [6, 7].

3 Conclusion and discussion

D_s mesons and Λ_c baryons are systematically studied in the mass loaded flux tube model. The study indicates that all Λ_c^+ baryons and D_s mesons in the 2008 review by the Particle Date Group are well described in the model. The baryons and mesons have the "same" structure and dynamics. The fitted parameters are similar for both the D_s mesons and the Λ_c baryons. The study of other heavy-light hadrons has not been described here.

The "diquark" hypothesis in Λ_c baryons is reasonable. If $\Lambda_c(2765)^+$ is an orbitally excited baryon, it is likely that $J^P = \frac{3}{2}^+$ Λ_c^+. If $\Lambda_c(2765)^+$ is an orbitally excited Σ_c, there ought to be another $J^P = \frac{3}{2}^+$ Λ_c^+ with mass ≈ 2770 MeV. In the model, a $J^P = \frac{1}{2}^+$ $\Lambda_c doesnotexist(2775)$.

Our study shows that higher excited D_s mesons have lower masses compared with most previous predictions, which may indicate some unclear features of the quark-antiquark potential existing in D_s. If $D_{sJ}(2632)^+$ exists, it may be a 1^-

$$\left(j^P = \frac{3}{2}^- \text{ or } 1^3D_1\right)$$

orbitally excited D_s. $D_s1(2700)^{\pm}$ is possibly the 1^- (2^3S_1) D_s, and $D_{sJ}(2860)$ is the excellent candidate for $3^-(1^3D_3)$ D_s.

The mixing effect plays an important role in the hadron spectrum and the hadron decay, etc. In some cases, the mixing effects may be the origin of the "exotic" properties of an observed state. If a physical state is a mixed state, it is necessary to study the detail of the mixing. Unfortunately, the mixing effect has not been studied systematically. Instead, the "exotic" interpretations beyond the conventional quark model for the "exotic" states are usually invoked. The exploration of the "exotic" states inside the conventional quark model deserves further study.

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