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Study of excited D_s mesons*

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Abstract The spectrum of D_s mesons is systematically studied in a semi-classic mass loaded flux tube model. D_s in D-wave multiplets is predicted to have lower masses in comparison with most theoretical predictions. $D_{sJ}(2632)^+$, $D_{s1}(2700)^{\pm}$, $D^{\star}_{sJ}(2860)^+$ and $D_{sJ}(3040)^+$ are interpreted in the constituent quark model.

Key words flux tube model, charmed strange mesons

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1 Introduction

In past years, the observation of some new D_s mesons and the relevant confusions to them gain great interest. A D_s meson is a heavy-light system, both the heavy quark symmetry and the light quark chiral symmetry exhibit their features in this system. So far, D_s mesons have been systematically studied in the relativized quark model [1–3], the heavy quark symmetry theory [4], the relativistic quark model [5], the lattice QCD theory [6], the chiral quark model [7], the constituent quark model (with heavy quark symmetry and chiral symmetry) [8–10], the relativistic chiral quark model [11, 12], the mass loaded flux tube model [13–15], the coupled channels model [16–19], and some other models [20, 21]. However, the predicted masses of the higher orbitally excited states seem to be overestimated in most models.

The semi-classical mass loaded flux tube model was studied 20 years ago [22]. In this model, a meson is a system with a massive quark m_1 and a massive anti-quark m_2 connected by a flux tube with universal constant tension T rotating with angular momentum L. The flux tube is responsible for the color confinement. This model was recently exploited in Ref. [23], where light mesons and baryons have been studied and well classified. The heavy-light hadron has not been analyzed, but an approximate mass formula was deduced [23]

$$E=M+\sqrt{\frac{\sigma L}{2}}+2^{\frac{1}{4}}\kappa L^{-\frac{1}{4}}m^{\frac{3}{2}}. \qquad (1)$$

The parameters were given in Ref. [23], the spin-orbit interactions were ignored in the formula.

In order to take into account the spin-orbit interactions, Eq. (1) was extended in Ref. [14]

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

In the fitting process in Ref. [14], four P-wave D mesons and two P-wave D_s mesons ($D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$) were used inputs. However, some P-wave mesons of them are mixed states, the approximation used there has to be improved.

2 Excited D_s mesons

2.1 New observed D_s

For the D_s or D_s-like states listed in the 2008 Review of Particle Physics by the PDG [24], the S-wave D_s mesons have been identified, and the P-wave D_s mesons are believed to be established though there are controversial interpretations to $D^{\star}_{s0}(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$. Some D_s candidates listed by PDG and some recently observed D_s candidates have not been identified. One confusion to identify these states is their lower masses compared with most theoretical predictions.

$D_{s1}(2700)$ was first observed by Belle [25, 26] in

$$B^+\rightarrow\bar{D}^0D_{s1}\rightarrow\bar{D}^0D^0K^+$$

with $M=2715\pm11^{+11}_{-14}$ and $\Gamma=115\pm20^{+36}_{-32}$ MeV.

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X(2690) was also reported by BABAR [27], but the significance of the signal was not stated.

$D^{\star}_{s1}(2710)^{\pm}$ was recently observed by BABAR [28] in

$$e^{+}+e^{-}\rightarrow D^{\star}_{s1}(2710)^{\pm}X\rightarrow D^{\star}KX$$

with $M=2710\pm2_{\rm stat}(^{+12}_{-7})_{\rm syst}$ MeV and $\Gamma=149\pm7_{\rm stat}(^{+39}_{-52})_{\rm syst}$ MeV.

These three experiments are believed to indicate the same state. For its $J^{P}=1^{-}$, this state was interpreted a mixture of the $2^{3}S_{1}$ and the $1^{3}D_{1}$ [29], the $1^{-}(1^{3}D_{1})$ [30], or the $2^{3}S_{1}$ [14, 15].

$D_{sJ}(2860)$ was first reported by BABAR [27] in

$$D_{sJ}(2860)\rightarrow D^{0}K^{+},\ D^{+}K^{0}_{s}$$

with $M=2856.6\pm1.5$ (stat)±5.0 (syst) and $\Gamma=48\pm7$ (stat) ±10 (syst) MeV. This state has natural spin-parity: $J^{P}=0^{+},\ 1^{-},\ \cdots$, and was explained as the first radial excitation of the $D^{\star}_{s0}(2317)$ [19, 30] or the $3^{-}(1^{3}D_{3})$ [14, 15, 30, 31].

$D^{\star}_{sJ}(2860)^{+}$ was recently observed by BABAR [28] in

$$e^{+}+e^{-}\rightarrow D^{\star}_{sJ}(2860)^{+}X\rightarrow D^{\star}KX,$$

with $M=2862\pm2_{\rm stat}(^{+5}_{-2})_{\rm syst}$ MeV and $\Gamma=48\pm3_{\rm stat}\pm6_{\rm syst}$ MeV. Obviously, the observation of $D_{sJ}(2860)\rightarrow D^{\star}K$ by BABAR rules out the possibility of 0^{+}.

$D_{sJ}(2632)^{+}$ is a surprisingly narrow signal which was first reported by SELEX [32] in

$$D^{+}_{sJ}(2632)\rightarrow D^{+}_{s}\eta\ ,\ D^{0}K^{+}$$

with $M=2632.5\pm1.7$(stat)±5.0(syst) and $\Gamma<17$ MeV with 90% confidence level. This state has an exotic relative branching ratio $\Gamma(D^{0}K^{+})/\Gamma(D^{+}_{s}\eta)=0.16\pm0.06$. Its decay favors the $D_{s}\eta$ mode over the DK mode, but the two channels share the same quark flavors and phase space. This signal was interpreted the conventional $1^{-}(2^{3}S_{1})$ D_{s} [33, 34], the four-quark state [35, 36]. In Ref. [37], we argued that this state seems not the $1^{-}(2^{3}S_{1})$ D_{s} and it is very possibly the $1^{-}(1^{3}D_{1})$ D_{s} [15]. However, this state has not been observed by BABAR, FOCUS or Belle. It seems that this state is excluded, which should be definitely confirmed by more experiments.

$D^{\star}_{sJ}(3040)^{+}$ was recently observed by BABAR [28] in

$$e^{+}+e^{-}\rightarrow D^{\star}_{sJ}(3040)^{+}X\rightarrow D^{\star}KX,$$

with $M=3044\pm8_{\rm stat}(^{+30}_{-5})_{\rm syst}$ MeV and $\Gamma=239\pm35_{\rm stat}\pm(^{+46}_{-42})_{\rm syst}$ MeV. The non-observation of $D_{sJ}(3040)^{+}\rightarrow DK$ and the angular analysis suggest an unnatural parity: $J^{P}=0^{-},\ 1^{+},\ 2^{-},\ \cdots$. This state was interpreted the radially excited 1^{+} $j^{P}=\frac{1}{2}^{+}$ D_{s} [15].

2.2 Orbitally and radially excited D_s

As well known, the mesons may be named in different ways. In the nonrelativistic quark model, the mesons are usually named by their quantum numbers $n^{2S+1}L_{J}$, where n is the principle quantum number, S is the total spin, L is the orbital angular momentum, and J is the total angular momentum. In most quark models, the interactions between the quark and the antiquark include the spin-independent confinement interaction, the spin-dependent interactions (spin-orbit interaction, color hyperfine interaction) and some other interactions [1, 38–40]. The spin-orbit interaction consists of a color-magnetic piece and a Thomas-precession piece. The spin-orbit interaction is often considered the dominant one except for the confinement interaction. In Ref. [14], the spin-orbit interaction is therefore approximated an $\vec{L}\cdot\vec{S}$ coupling, while other spin-dependent interactions were ignored.

In heavy quark effective field theory, the mesons are usually named by their quantum numbers nj^{P}, where j is the total angular momentum of the light degrees of freedom. Accordingly, the spin-orbit interactions may be approximated a $\vec{J}_{l}\cdot\vec{J}_{h}$ coupling. This approximation was successfully employed to study Λ_{c} baryons in Ref. [41]. However, in the infinite heavy quark limit, the hyperfine splitting effects vanish in D_{s}. In our previous analysis, the spectrum of D and D_{s} mesons is difficult to be reproduced with the approximation of the $\vec{J}_{l}\cdot\vec{J}_{h}$ coupling.

In the P-wave multiplets, there is mixing between the ${}^{3}P_{1}$ and the ${}^{1}P_{1}$. Similar mixing occurs between the ${}^{3}D_{2}$ and the ${}^{1}D_{2}$. Therefore, the physical P-wave 1^{+} and D-wave 2^{-} state is the mixed state. The detail of the mixing could be discovered by their spectra and decay features. In the fitting process, these mixed states are not good candidates of the inputs if the detail of the mixing is not clear. In Ref. [42], we improved the analysis of D_{s}.

In our analysis, $D_{s2}(2573)^{\pm}$, $D_{sJ}(2632)$ and $D_{sJ}(2860)$ are used as inputs [15, 42], while $D^{\star}_{s0}(2317)^{\pm}$, $D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$ are not used. After fixing $\sigma=1.10$ GeV^{2} through other theoretical studies, $M_{c}=1.354$ GeV, $m_{s}=0.462$ GeV and $a=0.044$ GeV were obtained through a minimum of the mean square error of the mass of these input states. These parameters are comparable with those in most quark models. The results of the spectrum of the orbitally excited D_{s} mesons are listed in the table in Ref. [42].

For the radially excited D_s mesons, the Regge trajectories phenomenology are employed. As stated in Ref. [43], in the mass region up to $M < 2400$ MeV, the radially excited mesons have Regge phenomenology on (n, M^2)-plots

$$M^2 = M_0^2 + (n-1)\mu^2, \tag{3}$$

where M_0 is the mass of the basic meson, n is the principle quantum number, and μ^2 is the slope parameter of the trajectory.

The assignments of $D_{s1}(2700)^{\pm}$ and $D_{sJ}(3040)^{+}$ with radially excited 1^- (2^3S_1) and $1^+ \left(\frac{1}{2}^+\right)$ D_s mesons, respectively, are consistent with the Regge phenomenology on (n, M^2)-plots

$$M^2(D_{s1}(2700)^{\pm}) - M^2(D_s^{\star}(2112)^{\pm}) = 2.78\ \text{GeV}^2,$$
$$M^2(D_{sJ}(3040)^{+}) - M^2(D_{s0}^{\star}(2460)^{\pm}) = 3.19\ \text{GeV}^2.$$

3 Conclusions

In summary, orbitally excited D_s mesons are studied in the mass loaded flux tube. The predicted masses of the P-wave and the D-wave D_s are much lower in comparison with most other theoretical predictions. The newly observed D_s mesons are interpreted. In our opinion, the "exotic" explanations of the newly observed states beyond the normal meson explanation may not be necessary. Our interpretation of those states are:

1) If $D_{sJ}(2632)^{+}$ exists, it seems not the radially excited 1^- 2^3S_1 D_s, it is very possibly the 1^- (1^3D_1) D_s.

2) $D_{s1}(2700)^{\pm}$ is very possibly the $1^-(2^3S_1)$ D_s.

3) If $D_{sJ}(2860)$ and its decay features are confirmed, it must be the 3^- 1^3D_3 D_s.

4) It is very likely that $D_{sJ}(3040)^{+}$ is the radially excited 1^+ $j^P = \frac{1}{2}^+$ D_s.

The spectra has been computed while the decay properties have not been explored in our work. Furthermore, the detail of the mixing of some states has not been studied. Only after we have well known the mixing effects, can we have a clear picture about D_s spectroscopy. More experiments and further theoretical studies inside the conventional quark model are required.

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