Implications to c$s$ assignments of $D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$

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Possible assignments of $D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ in the conventional quark model are analyzed. The study indicates that both the orbitally excited $c$s and the radially excited $c$s are possible. Some implications to these assignments are explored. If $D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ are the orbitally excited D-wave $1^- (j^P = \frac{3}{2}^-)$ and $3^- (j^P = \frac{5}{2}^-)$, respectively, another orbitally excited D-wave $2^- D_s, D_{s2}(2800)$, is expected. If $D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ are the first radially excited $1^- (j^P = \frac{3}{2}^-)$ and $0^+ (j^P = \frac{4}{2}^+)$, respectively, other two radially excited $0^- D_{s}'(2582)$ and $1^+ D_{s1}'(2973)$ are expected. $D_{s2}(2800)$ and $D_{s1}'(2973)$ are mixing states. The chiral doubling relation may exist in radially excited $D_s$, the splitting between the parity partners (the $0^-$ and the $0^+$) is $\approx 280$ MeV.

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I. INTRODUCTION

Heavy-light($Q\bar{q}$) mesons lie between the light ($q\bar{q}$) mesons and the heavy $QQ$ mesons. Both the heavy quark symmetry and the light quark chiral symmetry apply in this energy region. These symmetries (symmetry violations) may result in some special features to the spectrum, decay and production of the heavy-light mesons. The study of heavy-light mesons is helpful to detect the properties of quark dynamics.

Heavy-light mesons have been systematically explored in relativized quark model $^{[1,2]}$, heavy quark symmetry theory $^{[3,4]}$, relativistic quark model $^{[5,6]}$, chiral quark model $^{[7,8]}$, lattice $^{[9]}$, coupled channels models $^{[10,11]}$ and other models $^{[12,13,14]}$. For most heavy-light mesons, theoretical predictions of the masses and the decay characters are comparable with experiments.

In recent years, some "exotic" heavy-light mesons have been observed. For the "exotic" mesons, the measured masses or the observed decay properties are very different with theoretical predictions. So far, no "exotic" charmed meson($c\bar{q}(q = u, d))$ has been reported, and only "exotic" charmed strange mesons($c\bar{s}$) have been observed $^{[15]}$.

$D_{s0}(2317)^\pm$ was firstly observed by BaBar $^{[16]}$ in $D_{s0}(2317) \rightarrow D_s^+ \pi^0$ with mass near 2.32 GeV, $\approx 40$ MeV below $DK$ threshold. It has full width $\Gamma < 3.8$ MeV at 95% confidence level. This state was subsequently confirmed by CLEO $^{[17]}$ and BELLE $^{[18]}$. For the lower mass and the narrower width, controversial interpretations of this state were proposed.

$D_{s1}(2460)^\pm$ was firstly reported by CLEO $^{[17]}$ in $D_{s1}(2460)^\pm \rightarrow D_s^*\pi^0$. It was also observed by BELLE $^{[18]}$ and BaBar $^{[19]}$. This state has mass 2459.6 $\pm$ 0.6 MeV, $\approx 50$ MeV below $D^*K$ threshold, and full width $\Gamma < 3.5$ MeV at 95% CL. Similar to $D_{s0}(2317)^\pm$, the interpretations of $D_{s1}(2460)^\pm$ are of controversial.

Though $D_{s0}(2317)^\pm$ and $D_{s1}(2460)^\pm$ have "exotic" features, their exotic features could be explained in the traditional $c\bar{s}$ quark model. At present, most people believe that these two states belong to the P-wave multiplets of the $D_s$. They are thought of as the chiral doubler of $D_s(1969)^\pm$ and $D_s(2112)^\pm$. It is very possible that the lowest S-wave and P-wave multiplets of $D_s$ have been established.

While the P-wave multiplets have been filled, the higher $D_s$ are the D-wave $c\bar{s}$ or the radially excited $c\bar{s}$.

Very recently, two new states with higher energy were observed. $D_{s1}(2700)^\pm$ was firstly observed by Belle $^{[22]}$ in $B^+ \rightarrow D^0 D_{s1} \rightarrow D^0 D^0 K^+$ with $M = 2715 \pm 11_{-14}^{+11}$ and $\Gamma = 115 \pm 20_{-32}^{+36}$ MeV. The reported mass and decay width changes a little in the published paper $^{[23]}$. $X(2690)$ was also reported by Babar $^{[24]}$, but the significance of the signal was not stated. This state is included in PDG $^{[15]}$ with $M = 2690 \pm 7$ MeV, $J^{PC} = 1^-\cdot$ and full width $\Gamma = 110 \pm 27$ MeV.

$D_{sJ}(2860)$ was firstly reported by BaBar $^{[24]}$ in $D_{sJ}(2860) \rightarrow D^0 K^+ + D^+ K^0_s$ with $M = 2856.6 \pm 1.5(stat) \pm 5.0(syst)$ and $\Gamma = 48 \pm 7(stat) \pm 10(syst)$ MeV. It has natural spin-parity: $J^{PC} = 0^+, 1^-, \cdots$.

Before we proceed with the analysis of these two states, a brief theoretical introduction to the features of the $D_s$ mesons is suitable. When we have a look at previous theoretical computations, we notice that two kinds of classification schemes about the $D_s$ are popularly employed: the $D_s$ is classified by $2S+1L_J$ $^{[25]}$ or by $jL_j$ (where the HQET was incorporated in and $j$ is the total momentum of the light degree of freedom) $^{[4,5,10,11]}$. That is to say, two different bases of the wave functions of $D_s$ are employed. The relations between these two bases are determined by the Clebsch-Gordan coefficients $^{[25]}$. In the D-wave multiplets of $D_s$, the $^2D_1$ and the $^2D_3$ in the $jL_j$ basis correspond to the $^2D_1$ and the $^2D_3$ in the
The features of the pure states may be simple, but the features of the mixing states are much more complicated. Only when the exact components of the mixing states are clear, we can understand the features of these states. Unfortunately, the exact components of some observed states are not well understood. Therefore, people is usually careful with his conclusion when he observes a new state, which may requires much more explorations. In this Letter, the decay features of $D_s$ are touched and the spectrum is concentrated on.

The D-wave multiplets of $D_s$ and the radially excited $D_s$ have been studied for a long time. Though the predictions of the masses or the decay features are sometimes different in different models, these theoretical explorations provide much information about the quark dynamics.

The $1^3D_1$ is predicted to have mass $\approx 2900$ MeV [1, 5] and total decay width $\Gamma = 331$ MeV [20]. The transition $D_s(1^{3}D_1) \to DK$ is predicted to have decay width 26.1 MeV in Ref. [3], and broader width 120 MeV in Ref. [21].

The $1^3D_3$ is expected to have mass $\approx 2920$ MeV [1, 5] and total width $\Gamma = 222$ MeV [20]. The predicted decay width of $D_s(1^{3}D_3) \to DK$ in Ref. [5] is different with that in Ref. [21]. It is 11.4 MeV in Ref. [5] and 82 MeV in Ref. [21].

The lowest three radially excited states are the $2^1S_0$, the $2^3S_1$ and the $2^3P_0$. The $2^3S_1$ is predicted to have mass $\approx 2700$ MeV [1, 4] and total width $\Gamma = 105$ MeV [21]. The predicted decay width of $D_s(2^{3}S_1) \to DK$ in Ref. [5] (21.1 MeV) is similar to that in Ref. [21] (17 MeV).

The $2^3P_0$ is predicted to have mass $\approx 3067$ MeV [5] and total width $\Gamma = 90$ MeV [21]. The decay $D_s(2^{3}P_0) \to DK$ is predicted to have width 74.1 MeV [5] or 80 MeV [21].

Based on these theoretical explorations and further analyses, some assignments of $D_{s1}(2700)\pm$ and $D_{sJ}(2860)$ have been suggested. In existing literatures, $c\bar{s}$ assignments are most advocated. These assignments will be examined in a phenomenological way. Especially, some implications relevant to these assignments are explored.

| Candidates $J^P$ $j^P$ $n^{2S+1}L_J$ | [1] | [4] | [5] | [14] |
|-----------------------------|-----|-----|-----|-----|
| $D_{s1}(2700)$ 1$^-$ $\frac{1}{2}^-$ 1$^-$D$_{1}$ | 2.90 | 2.913 | 2.714 |
| $? $ 2$^-$ ($\frac{3}{2}^-$) 1$^-$D$_{1}$ | - | 2.900 | 2.789 |
| $? $ 2$^-$ ($\frac{5}{2}^-$) 1$^-$D$_{1}$ | - | 2.953 | 2.827 |
| $D_{sJ}(2860)$ 3$^-$ $\frac{5}{2}^-$ 1$^-$D$_{3}$ | 2.92 | 2.925 | 2.903 |
| $? $ 0$^-$ $\frac{1}{2}^-$ 2$^+$S$_{0}$ | 2.67 | 2.670 | 2.700 |
| $D_{s1}(2700)$ 1$^-$ $\frac{1}{2}^-$ 2$^+$S$_{0}$ | 2.73 | 2.716 | 2.806 |
| $D_{sJ}(2860)$ 0$^+$ $\frac{1}{2}^+$ 2$^+$P$_{0}$ | - | 3.067 | - |
| $? $ 1$^+$ ($\frac{1}{2}^+$) 2$^+$P$_{1}$ | - | 3.114 | - |
| $? $ 1$^+$ ($\frac{3}{2}^+$) 2$^+$P$_{1}$ | - | 3.165 | - |
| $? $ 2$^+$ $\frac{3}{2}^+$ 2$^+$P$_{2}$ | - | 3.157 | - |

TABLE I: Spectrum of the 1D, the 2S and the 2P $D_s$(GeV).

II. POSSIBLE ASSIGNMENTS OF $D_{s1}(2700)\pm$ AND $D_{sJ}(2860)$

Comparing with the theoretical predictions of the masses and the decay features, it is natural to explain $D_{s1}(2700)\pm$ and $D_{sJ}(2860)$ as the D-wave $D_s$ or the radially excited $D_s$.

In Ref. [21], the authors believe that $D_{s1}(2700)\pm$ is probable the $1^-(1^3D_1)$ $D_s$ through the study of its strong decay. If this assignment is true, the mass of $D_{s1}(2700)\pm$ is $\approx 200$ MeV lower than theoretical predictions [1, 5]. In Refs. [21, 27], $D_{sJ}(2860)$ is interpreted as the $3^-(1^3D_3)$ $D_s$.

As the candidates of the radial excitations, $D_{s1}(2700)\pm$ is interpreted as the $1^-(2^3S_1)$ $D_s$ [21] (first radial excitation of the $D_s(2112)^\pm$), and $D_{sJ}(2860)$ is interpreted as the $0^+(2^3P_0)$ $D_s$ [26, 28] (first radial excitation of the $D_{s0}(2317)^\pm$). If $D_{sJ}(2860)$ is the $0^+(2^3P_0)$ $D_s$, its mass is also $\approx 200$ MeV lower than theoretical prediction [5].

Theoretical predictions of the D-wave and the radially excited S, P-wave $D_s$ are summarized in Table.??. To compare theoretical predictions explicitly, we show the results obtained in Refs. [1, 3, 5, 14]. Both the notation $n^{2S+1}L_J$ [1, 14] and the notation $j^P$ [4, 5] are employed for the classification of $c\bar{s}$. Accordingly, all the quantum numbers $J^P, j^P$ and $n^{2S+1}L_J$ are listed. A parenthesis is put on the $j^P$ for the 1D and the 2P $D_s$ states to emphasize that there is no one-to-one correspondence between the $n^{2S+1}L_J$ and the $1^3L_J$ or $j^P$ classification scheme. The dash "-" indicates that the mass of the corresponding state has not been predicted, and the "?" indicates that there is not observed candidate corresponding to the assignment. Possible assignments of $D_{s1}(2700)\pm$ and $D_{sJ}(2860)$ are denoted.

These two states seem a little "exotic" to the assignments. On one hand, some experimentally measured decay widths deviate largely from theoretical predictions. On the other hand, the masses of $D_{s1}(2700)\pm$ and $D_{sJ}(2860)$ are $\approx 200$ MeV lower than the predictions of the $1^-(1^3D_1)$ and the $0^+(2^3P_0)$ $D_s$.

These "exotic" features imply that existing models may not be valid, or models are valid but need improve-
ment, or the interpretations of the states are incorrect. Therefore it is necessary to study the "exotic" features.

The character of lower masses is well explained in the coupled channels analysis [23]. This feature is also well explained in a mass loaded flux tube model [14, 29]. In the model, the orbitally excited masses of $D$ and $D_s$ are computed through

$$E = M + \sqrt{\frac{\sigma L}{2} + 2\frac{\kappa L}{r} - 2m \frac{\Delta}{r} + aL \cdot \vec{S}}. \tag{1}$$

The predicted masses for the $1^- (1^3 D_1) \approx 2714 \pm 30$ MeV and the $3^- (1^3 D_3) \approx 2903 \pm 40$ MeV agree well with that of $D_{s1}(2700)$ and $D_{sJ}(2860)^\pm$ states, respectively.

The masses of the $1^3 D_2 (\approx 2789 \pm 44$ MeV) and the $1^1 D_2 (\approx 2827 \pm 44$ MeV) are predicted in Ref. [14]. Concern about the mixing between the $3^1 D_3$ and the $1^3 D_2$, a $2^- D_2$ charmed strange meson (denoted as $D_{s2}(2800)$) with mass $\approx 2800$ MeV is expected.

The widths of some transitions of the $D_{s2}(2800)$ (2900 MeV) and the $D_{s1}(2860)$ have been computed in Ref. [3]. In terms of Eq. (33) in Ref. [3], the new results are obtained in Table III with mass correction considered, where $\ell$ is the angular momentum of the final light mesons.

$D_{s2}(2800)$ is the mixing of the $\frac{1}{2} D_2$ and the $\frac{3}{2} D_2$. When the mixing effect is taken account of, the decay channel $D_{s2}(2800) \rightarrow D^* K$ has width $\approx 11 - 37$ MeV and the channel $D_{s2}(2800) \rightarrow D^*_s \eta$ has width $\approx 2 - 17$ MeV.

Radial excitation of $D$ and $D_s$ has not yet been discovered, but the mass of some radial excitations have been computed in models. In what follows, we avoid the model dependent computation of the spectrum and proceed with a phenomenological analysis.

As explored in Ref. [30], in the mass region up to $M < 2400$ MeV, a mass equation about the radially excited mesons holds with a good accuracy (trajectories on $(n, M^2)$-plots)

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

where $M_0$ is the mass of the basic meson, $M$ is the mass of the radial excitation, $n$ is the radial quantum number, and $\mu^2$ is the slope parameter of the trajectory (approximately the same for all trajectories).
The total width of $D_{13}^*(2973)$ is broad. For separate channel, the channel $D_{13}^*(2973) \to D^*K$ has width $\approx 37 - 72$ MeV, the channel $D_{13}^*(2973) \to D_3^0K$ has width $\approx 6 - 43$ MeV and the channel $D_{13}^*(2973) \to D_s^*\eta$ has width $\approx 5 - 45$ MeV.

Of course, once $D_{s1}(2700)^\pm$ is pinned down as the $1^{-}(2^{3}S_1)$, the exotic $D_{sJ}(2632)^+$ reported by SELEX [31] becomes a supernumerary one. In Ref. [32], the exotic feature of the mass of $D_{sJ}(2632)^+$ has been mentioned in a similar way. How to put this state into the $D_s$ zoo deserves more exploration.

III. DISCUSSIONS AND CONCLUSIONS

Some features of $D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ are really different with previous predictions. In our analysis, these features could be explained in the conventional quark model. "Exotic" interpretation outside of the $c\bar{s}$ assignments may not be necessary.

$D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ may be the orbitally excited D-wave $1^{-}(J^P = \frac{1}{2}^-)$ and $3^{-}(J^P = \frac{3}{2}^-)$, respectively. In these assignments, another $D_{s2}(2800)$ with mass $\approx 2800$ MeV is expected. It is the mixing of the $^3D_2$ and the $^1D_1$ (or the mixing of the $^3D_2$ and the $^5D_2$). The decay $D_{s2}(2800) \to D^*K$ has width $\approx 11 - 37$ MeV and the channel $D_{s2}(2800) \to D_s^*\eta$ has width $\approx 2 - 17$ MeV.

$D_{s1}(2700)^\pm$ and $D_{sJ}(2860)$ are very possible the first radially excited $1^{-}(J^P = \frac{1}{2}^-)$ and $0^+(J^P = \frac{1}{2}^+)$, respectively. In this case, other two radially excited $0^-(D_{sJ}(2582)$ and $1^+D_{sJ}(2973)$ are expected. These two states are the radial excitations of $D_s(1699)^\pm$ and $D_{sJ}(2460)^\pm$. The chiral doubling relation may exist in radially excited $D_s$, the splitting between the parity partners (the $(0^-,1^-)$ and the $(0^+,1^+)$) is $\approx 280$ MeV. $D_{s1}(2973)$ has a broad total width.

The component of an observed mixed state is usually not clear, it is an important origin to the "exotic" properties of the observed state. How to explain an observed state in terms of the features of the pure states deserves more exploration.

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