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Interpretation of $D_{sJ}(2632)^+$, $D_{s1}(2700)^{\pm}$, $D^*_{sJ}(2860)^+$, and $D_{sJ}(3040)^+$

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D_s mesons are investigated in a semiclassic flux tube model where the spin-orbit interaction is taken into account. Spectrum of D-wave D_s is predicted. The predicted spectrum is much lower than most previous predictions. Analysis of some D_s candidates is made. $D_{sJ}(2632)^+$ may be a 1^- ($j^P=\frac{3}{2}^-$ or $1\,^3D_1$) orbitally excited D_s meson if it really exists. $D_{s1}(2700)^{\pm}$ is very possibly the first radially excited 1^- ($j^P=\frac{1}{2}^-$ or $2\,^3S_1$) D_s meson [the first radial excitation of $D_s^{\star\pm}(2112)^0$]. $D^{\star}_{sJ}(2860)^+$ should be a 3^- ($j^P=\frac{5}{2}^-$ or $1\,^3D_3$) orbitally excited D_s meson, and $D_{sJ}(3040)^+$ is the first radially excited 1^+ ($j^P=\frac{1}{2}^+$) D_s meson. Our conclusions are consistent with the latest *BABAR* experiment.

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I. INTRODUCTION

D_s mesons have gained great deal of interest in recent years. More and more D_s mesons were observed by experiments, and many theoretical explorations were triggered. However, some candidates have not been pinned down; their features are not yet clear.

$D^{\star}_{s0}(2317)^{\pm}$ was first observed by *BABAR* [1] in $D^{\star}_{s0}(2317)\to D_s^+\pi^0$ with mass near 2.32 GeV in 2003; $D_{s1}(2460)^{\pm}$ was also first reported by CLEO [2] in $D_{s1}(2460)^{\pm}\to D_s^{\star}\pi^0$ in 2003. Though there are controversial interpretations of these two states, $D^{\star}_{s0}(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$ are believed to be the 0^+ and 1^+ D_s mesons, respectively.

Another surprisingly narrow charmed strange meson, $D_{sJ}(2632)^+$, was reported by SELEX [3] in 2004 in

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

with $M=2632.5\pm1.7(\text{stat})\pm5.0(\text{syst})$ and $\Gamma<17$ MeV with 90% confidence level. This state has an exotic relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_s^+\eta)=0.14\pm0.06$. The decay favors the $D_s\eta$ mode over the DK, but the two channels share the same quark flavors and similar phase space.

Two new D_s mesons were observed in 2006. $D_{s1}(2700)^{\pm}$ was first observed by Belle [4] in $B^+\to\bar{D}^0D_{s1}\to\bar{D}^0D^0K^+$ with $M=2715\pm11^{+11}_{-14}$ and $\Gamma=115\pm20^{+36}_{-32}$ MeV. The reported mass and decay width changes a little in the published paper [5]. $X(2690)$ was reported by *BABAR* [6], but the significance of the signal was not stated. This state is included in PDG08 [7] with $M=2690\pm7$ MeV, $J^P=1^-$, and full width $\Gamma=110\pm27$ MeV.

$D_{sJ}(2860)$ (not listed by the PDG08) was first reported by *BABAR* [6] in $D_{sJ}(2860)\to D^0K^+, D^+K^0_s$ with $M=2856.6\pm1.5(\text{stat})\pm5.0(\text{syst})$ and $\Gamma=48\pm7(\text{stat})\pm10(\text{syst})$ MeV. It was supposed to have natural spin-parity: $J^P=0^+,1^-,\ldots$. This state has not been confirmed by Belle; therefore, whether it exists is not clear. In fact, there is another possibility for the nonobservation of $D_{sJ}(2860)$ by Belle. The nonobservation may indicate a high spin for $D_{sJ}(2860)$ that suppresses its production in B decays.

Very recently, *BABAR* [8] reported the study of D_{sJ} decays to $D^{\star}K$ in inclusive e^+e^- interactions. In their report, they observed the decays $D^{\star}_{s1}(2710)^+\to D^{\star}K$ and $D^{\star}_{sJ}(2860)\to D^{\star}K$. They performed an angular analysis of these two states and measured their branching fractions relative to the DK final state

$$\frac{\mathcal{B}(D^*_{s1}(2710)^+\to D^*K)}{\mathcal{B}(D^*_{s1}(2710)^+\to DK)}=0.91\pm0.13_{\text{stat}}\pm0.12_{\text{syst}}, \tag{1}$$

$$\frac{\mathcal{B}(D^*_{sJ}(2860)^+\to D^*K)}{\mathcal{B}(D^*_{sJ}(2860)^+\to DK)}=1.10\pm0.15_{\text{stat}}\pm0.19_{\text{syst}}. \tag{2}$$

The new experiment will definitely give more information about these two states. In the *BABAR* experiment, a new broad structure $[D_{sJ}(3040)^+]$ at a mass $3044\pm8(\text{stat})(^{+30}_{-5})(\text{syst})$ MeV with $\Gamma=(239\pm35(\text{stat})(^{+46}_{-42})\times(\text{syst}))$ is also observed.

So far, it is believed that the S-wave and the P-wave D_s mesons have been established. Resonance beyond the S-wave and the P-wave D_s has not yet been confirmed. How to put these new observed states in the D_s zoo or other family deserves systematic study. In this paper, we study the spectra of D_s mesons and classify these new states in an improved classic flux tube model.

The paper is constructed as follows. In the first section, we give a brief introduction to relevant experiments. D_s mesons are systematically studied in an improved classic flux tube model in Sec. II. In Sec. III, the new states are

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classified. Our conclusions and discussions are presented in Sec. IV.

II. D_s IN CLASSIC FLUX TUBE MODEL

The classic flux tube model was studied 20 years ago [9]. The quantization of this model was also performed though the procedure is a little complicated [10]. Selem and Wilczek studied the light hadrons in this classic flux tube model (mass loaded flux tube model) [11], where the spin-orbit interaction is ignored and the heavy-light hadrons have not investigated. The spin-orbit interaction was taken into account to study the D, D_s, and Λ_c [12,13], but the spin-orbit interaction was simplified as a simple $L \cdot S$ coupling. In fact, the spin-orbit interaction inspired by QCD was largely discussed in the literature [14–22]. The form in Ref. [21] will be employed in this paper.

In a relativized quark model, the quark-antiquark potential $V(\vec{r})$ inside mesons with one heavy quark was written as [21]

$$V(\vec{r}) = H^{\rm conf}_{q\bar{q}} + H^{\rm cont}_{q\bar{q}} + H^{\rm ten}_{q\bar{q}} + H^{\rm SO}_{q\bar{q}},$$

where the spin-orbit interaction is

$$H^{\rm SO}_{q\bar{q}} = H^{\rm SO+}_{q\bar{q}}(\vec{S}_q + \vec{S}_{\bar{q}}) \cdot \vec{L} + H^{\rm SO-}_{q\bar{q}}(\vec{S}_q - \vec{S}_{\bar{q}}) \cdot \vec{L}.$$

For mesons

$$H^{\rm SO+}_{q\bar{q}} = \left[\frac{2\alpha_s}{3r^3}\left(\frac{1}{m_q} + \frac{1}{m_{\bar{q}}}\right)^2 - \frac{1}{4r}\frac{\partial H^{\rm conf}_{q\bar{q}}}{\partial r}\left(\frac{1}{m_q^2} + \frac{1}{m_{\bar{q}}^2}\right)\right],$$

and

$$H^{\rm SO-}_{q\bar{q}} = \left(\frac{2\alpha_s}{3r^3} - \frac{1}{4r}\frac{\partial H^{\rm conf}_{q\bar{q}}}{\partial r}\right)\left(\frac{1}{m_q^2} - \frac{1}{m_{\bar{q}}^2}\right).$$

The mass of mesons is obtained from the Schrödinger equation where the eigenstates of (J^2, L^2, S^2, J_z) is employed. There is no mixing for ${}^3P_0$ and ${}^3P_2$, but there is a mixing between ${}^3P_1$ and ${}^1P_1$. These two mixed states are denoted as $({}^3P_1)'$ and $({}^1P_1)'$, respectively. The case is similar for the D-wave and F-wave mesons. In the limit where $m_Q \longrightarrow \infty$, we obtain the mass formulas

$$\begin{pmatrix} M_1 - H^+ & \frac{\sqrt{2}}{3}H^- \\ \frac{\sqrt{2}}{3}H^- & M_1 \end{pmatrix}\begin{pmatrix} {}^3P_1 \\ {}^1P_1 \end{pmatrix} = \begin{pmatrix} M({}^3P_1)' \\ M({}^1P_1)' \end{pmatrix} \quad (3)$$

for the P-wave multiplet and

$$\begin{pmatrix} M_2 - H^+ & \sqrt{\frac{2}{3}}H^- \\ \sqrt{\frac{2}{3}}H^- & M_2 \end{pmatrix}\begin{pmatrix} {}^3D_2 \\ {}^1D_2 \end{pmatrix} = \begin{pmatrix} M({}^3D_2)' \\ M({}^1D_2)' \end{pmatrix} \quad (4)$$

for the D-wave multiplet. In these equations, $H^{\pm}$ ($= \langle H^{\rm SO+}\rangle$) is the expectation value of the spatial part of $H^{\rm SO\pm}$ and M_L ($L = 1, 2$) is the center of mass of the multiplet which is independent of the spin-orbit interaction. In the framework of the $L \cdot S$ coupling scheme, the calculable $\langle H^{\rm SO+}\rangle \approx \langle H^{\rm SO-}\rangle$ (denoted as a) when the heavy quark effect is considered, and the difference of a among different orbits could be ignored.

Accordingly, the mass of all the mesons could be written as

$$M({}^{2S+1}L_J) = M_L + \xi_{L,S}a, \quad (5)$$

where $M({}^{2S+1}L_J)$ is the mass of the physical state and $\xi_{L,S}$ is the calculable coefficient.

In Table. I, the explicit $\xi_{L,S}$ for P-wave and D-wave mesons is estimated. The states with an upper prime correspond to the mixing physical states.

When Eq. (5) is compared with Eq. (3) in Ref. [12] [or Eq. (2) in Ref. [13]], it is reasonable to improve the formula of mass of the D_s meson in the classic flux tube model to

$$E = M_c + \sqrt{\frac{\sigma L}{2}} + 2^{1/4}\kappa L^{-1/4}m_s^{3/2} + \xi_{L,S}a, \quad (6)$$

where M_c is the c quark mass, m_s is the s quark mass, L is the angular momentum of the D_s, $\frac{\sigma}{2\pi}$ is the string tension T, $\kappa \equiv \frac{2}{3}\frac{\pi^{1/2}}{\sigma^{1/4}}$, and parameter a could be fixed through experimental data. Obviously, the first three terms on the right-hand side of Eq. (6) is the center of mass of the multiplet resulting from confinement, and the last term on the right-hand side of Eq. (6) results from the spin-orbit contribution.

The next step is to fix the parameters in Eq. (6). For this purpose, some states are used as inputs. As is well known, a scalar meson usually has special features, so the 0^+ $D^\star_{s0}(2317)^\pm$ is not used as an input. In the fitting procedure, $D_{s1}(2536)^\pm$, $D_{s1}(2460)^\pm$, $D_{s2}(2573)^\pm$, and $D^+_{sJ}(2860)$ are identified as the four states $({}^3P_1)'$, $({}^1P_1)'$, ${}^3P_2$, and ${}^3D_3$, respectively. The reason for the identification of $D^+_{sJ}(2860)$ is stated in the next section.

First, the a in Eq. (6) is fixed: $a = 0.05$ GeV, through the mean square of

$$\begin{aligned} &\Delta(M({}^3P_2) - M({}^3P_1)') = 0.04\ \text{GeV}, && a = 0.05\ \text{GeV}; \\ &\Delta(M({}^3P_2) - M({}^1P_1)') = 0.11\ \text{GeV}, && a = 0.05\ \text{GeV}; \\ &\Delta(M({}^3P_1)' - M({}^1P_1)') = 0.08\ \text{GeV}, && a = 0.06\ \text{GeV}. \end{aligned} \quad (7)$$

The other three parameters M_c, m_s, and σ cannot be fixed through the four states (only P wave and D wave). Since σ reveals the dynamics of confinement of the meson,

TABLE I. $\xi_{L,S}$ for P-wave and D-wave mesons.

State	$\xi_{L,S}$	State	$\xi_{L,S}$
$({}^3P_2)$	+1.00	$({}^3D_3)$	+2.00
$({}^3P_1)'$	+0.20	$({}^3D_2)'$	+0.46
$({}^1P_1)'$	−1.20	$({}^1D_2)'$	−1.46
$({}^3P_0)$	−2.00	$({}^3D_1)$	−3.00

it is reasonable to borrow its value from the other quark model (σ varies little in a different model). Here, $\sigma \approx 1.10\ \mathrm{GeV}^2$ [12,18] is employed. M_c and m_s are therefore determined as $M_c = 1.40$ GeV and $m_s = 0.42$ GeV. The parameters M_c, m_s, and a are comparable with Refs. [12,13].

With these parameters in hand, masses of other D wave D_s could be predicted. All the candidates of S-, P-, and D-wave D_s and their spectra are shown in Table. II. In the table, the predictions of the spectra in Refs. [18,23] are listed. The calculation was performed in a $^{2S+1}L_J$ scheme in Ref. [18], and the estimation was performed in a j^P scheme in Ref. [23]. The spectra of D-wave D_s obtained here is much lower than most theoretical predictions. Similar lower spectra was obtained in a relativistic chiral quark model 10 years ago [24,25]. In a popular viewpoint, the origin of the lower mass of $D^\star_{s0}(2317)^\pm$ and $D_{s1}(2460)^\pm$ is that coupled-channel effects can shift masses from naive quark model predictions by up to a couple hundred MeV. From our analysis, it is found that there is another possibility. A new feature of the confinement potential in a heavy-light system may result in a lower spectra.

In fact, it is very possible that $D_{s1}(2460)^\pm$ and $D_{s1}(2536)^\pm$ are not the $j^P = \frac{1}{2}^+$ 1^+ and the $j^P = \frac{3}{2}^+$ 1^+ D_s, respectively. The $j^P = \frac{1}{2}^+$ 1^+ D_s was predicted to have a large width in Ref. [23], while its full width is very small (< 3.5 MeV) in PDG08 [7]. $D_{s1}(2460)^\pm$ and $D_{s1}(2536)^\pm$ are mixing states of the $j^P = \frac{1}{2}^+$ 1^+ and the $j^P = \frac{3}{2}^+$ 1^+ D_s. Therefore, parentheses are also added to those mixed j^P states in Table. II.

III. $D_{sJ}(2632)^+$, $D_{s1}(2700)^\pm$, $D^\star_{sJ}(2860)^+$, AND $D_{sJ}(3040)^+$

A. $D_{sJ}(2632)^+$

$D_{sJ}(2632)^+$ was suggested to be a four-quark state in Refs. [26,27], and it was interpreted as a conventional $1^-(2^3S_1)$ $c\bar{s}$ in Refs. [28–30]. It was pointed out in Ref [31] that $D_{sJ}(2632)^+$ seems unlike the $1^-(2^3S_1)$ $c\bar{s}$. However, $D_{sJ}(2632)^+$ is not observed by *BABAR* [32], FOCUS, or Belle, and it seems that this state is excluded. In the semiclassic flux tube model, the 1^- ($\frac{3}{2}^-$ or 1^3D_1) D_s with mass 2.62 GeV is predicted. In a framework of $^3P_0$ pair creation model [33], the decay $D_{s1}(1^3D_1) \to D^0K$ of the predicted state is found to have width $\Gamma(D_{s1}(1^3D_1) \to D^0K) = 3.73$ MeV. It is very possible that $D_{sJ}(2632)^+$ is the 1^- 1^3D_1.

TABLE II. Spectrum of charmed strange mesons (GeV) with parameters $\sigma = 1.10\ \mathrm{GeV}^2$, $M_c = 1.40$ GeV, $m_s = 0.42$ GeV, and $a = 0.05$ GeV.

Candidates [7]	J^P	j^P	$n^{2S+1}L_J$	Ref. [18]	Ref. [23]	Our paper
$D_s^\pm(1969)$	0^-	$\frac{1}{2}^-$	1^1S_0	1.98	1.965	⋯
$D_s^{\star\pm}(2112)^0$	1^-	$\frac{1}{2}^-$	1^3S_1	2.13	2.113	⋯
$D^\star_{s0}(2317)^\pm$	0^+	$\frac{1}{2}^+$	1^3P_0	2.48	2.487	2.42
$D_{s1}(2536)^\pm$	1^+	$(\frac{3}{2}^+)$	$(1^3P_1)'$	2.57	2.535	2.53
$D_{s1}(2460)^\pm$	1^+	$(\frac{1}{2}^+)$	$(1^1P_1)'$	2.53	2.605	2.46
$D_{s2}(2573)^\pm$	2^+	$\frac{3}{2}^+$	1^3P_2	2.59	2.581	2.57
$D_{sJ}(2632)$	1^-	$\frac{3}{2}^-$	1^3D_1	2.90	2.900	2.62
?	2^-	$(\frac{5}{2}^-)$	$(1^3D_2)'$	⋯	2.913	2.81
?	2^-	$(\frac{3}{2}^-)$	$(1^1D_2)'$	⋯	2.925	2.70
$D_{sJ}(2860)$	3^-	$\frac{5}{2}^-$	1^3D_3	2.92	2.953	2.87

B. $D_{s1}(2700)^\pm$

There are three possible sets of experimental data for $D_{s1}(2700)^\pm$ as enumerated in the Introduction, and it is reasonable to regard them as the same state because they have the approximately equal mass and decay width. In Ref. [34], $D_{s1}(2700)^\pm$ was thought to be the $1^-(1^3D_1)$ D_s, which is ≈ 200 MeV lower than theoretical predictions [18,23]. $D_{s1}(2700)^\pm$ was interpreted as the $1^-(2^3S_1)$ D_s [35,36] [first radial excitation of the $D_s^\star(2112)^\pm$]. When the observed branching ratio [Eq. (1)] is compared with theoretical predictions [37], the $1^-(2^3S_1)$ assignment is preferred.

C. $D^\star_{sJ}(2860)^+$

$D^\star_{sJ}(2860)^+$ was once interpreted as a conventional $0^+(2^3P_0)$ $c\bar{s}$ [34,38], which is also ≈ 200 MeV lower than the theoretical prediction [23]. This state was interpreted as a conventional $3^-(1^3D_3)$ $c\bar{s}$ [34,36,39]. The observation of $D^\star_{sJ}(2860)^+ \to D^\star K$ [8] rules out the possibility of 0^+ (2^3P_0). In the meantime, the observed branching ratio [Eq. (2)] is in significant disagreement with theoretical predictions [35]. On the other hand, $\frac{\mathcal{B}(D^\star_{sJ}(2860)^+ \to D^\star K)}{\mathcal{B}(D^\star_{sJ}(2860)^+ \to DK)} = 1.23$ is obtained when $D^\star_{sJ}(2860)^+$ is treated as a 2^3S_1 [39], which is in agreement with Eq. (2). However, one expects this vector meson to have a considerably lower mass, around 2720 MeV [18,40], which makes the $D_{s1}(2700)^\pm$ a much better candidate. Because of these facts, the existence of two largely overlapping resonances at about 2.86 GeV (radially excited tensor 2^+ and radially excited scalar 0^+ $c\bar{s}$ states) was suggested [41]. It was argued that the possibility of 0^+ (2^3P_0) could not be ruled out now. In our analysis, $D^\star_{sJ}(2860)^+$ is an excellent candidate for the 3^- (1^3D_3) $c\bar{s}$.

D. $D_{sJ}(3040)^+$

Both the nonobservation of $D_{sJ}(3040)^+ \to DK$ and the angular analysis suggest an unnatural parity $J^P = 0^-, 1^+, 2^-, \ldots$ for $D_{sJ}(3040)^+$. In Ref. [23], the first radial excitation of the 1^+ ($j^P = \frac{1}{2}^+$) D_s (≈ 3.165 GeV) was predicted to have a large width $\Gamma \approx 210$ MeV, the first radial excitation of the 1^+ ($j^P = \frac{3}{2}^+$) D_s (≈ 3.114 GeV) was predicted to have width $\Gamma \approx 51$ MeV, and the F-wave D_s do not have large width. In Ref. [35], the mass of $D_s(2^3P_1)'$ was predicted around 2995 MeV. In Ref. [42], the radially excited "$^3P_1$" (1^+) and "$^1P_1$" (1^+) D_s were predicted to have mass 3082 and 3094 GeV, respectively. Therefore, it is reasonable to interpret $D_{sJ}(3040)^+$ as the first radially excited 1^+ ($j^P = \frac{1}{2}^+$) D_s [or the mixing of the radially excited 1^+ ($j^P = \frac{1}{2}^+$) and 1^+ ($j^P = \frac{3}{2}^+$), but mainly ($j^P = \frac{1}{2}^+$)].

In fact, $D_s^\star(2112)^\pm$, $D_{s1}(2460)^\pm$ [or $D_{s1}(2536)^\pm$], $D_{s1}(2700)^\pm$, and $D_{sJ}(3040)^+$ meet trajectories on the (n, M^2) plot: $M^2 = M_0^2 + (n-1)\mu^2$ [36,43],

$$M^2((D_{s1}(2700)^\pm) - (D_{s1}^\star(2112)^\pm) = 2.78\ \text{GeV}^2;$$

$$M^2((D_{sJ}(3040)^+) - (D_{s1}(2460)^\pm)) = 3.19\ \text{GeV}^2;$$

$$M^2((D_{sJ}(3040)^+) - (D_{s1}(2536)^\pm)) = 2.79\ \text{GeV}^2.$$

Some partners of these observed states are expected to exist. Two 2^- D-wave D_s may exist at 2.70 GeV and 2.81 GeV. The radially excited 1^+ and 2^+ D_s are expected to exist around 3.0 GeV.

IV. CONCLUSIONS AND DISCUSSIONS

D_s mesons are investigated in a semiclassic flux tube model. In this model, the classic flux tube is responsible for the confinement of quark-antiquark inside mesons. The spin-orbit interaction is involved through a deep investigation in the relativized quark model. A formula of the energy for heavy-light mesons is obtained. In terms of the formula, the spectra of D-wave D_s are predicted after some observed states are taken as inputs. The predicted spectra of D-wave D_s are much lower than most previous predictions.

In a popular viewpoint, it is believed that the origin of the lower mass of $D_{s0}^\star(2317)^\pm$ and $D_{s1}(2460)^\pm$ is that coupled-channel effects can shift their masses from naive quark model predictions by up to a couple hundred MeV. Our investigation indicates that the lower spectra of D-wave D_s may imply another possibility. There is a new feature for the quark-antiquark potential in the heavy-light system, which may result in a lower spectra.

The unidentified $D_{sJ}(2632)^+$, $D_{s1}(2700)^\pm$, $D_{sJ}^\star(2860)^+$, and $D_{sJ}(3040)^+$ are analyzed, and possible assignments to them are made. Our conclusions are consistent with the latest *BABAR* experiment.

$D_{sJ}(2632)^+$ is very likely the 1^- ($j^P = \frac{3}{2}^-$ or 1^3D_1) orbitally excited D_s meson with a narrow width if this state really exists.

$D_{s1}(2700)^\pm$ may be the 1^- ($j^P = \frac{1}{2}^-$ or 2^3S_1) D_s meson [the first radially excitation of $D_s^{\star\pm}(2112)^0$].

$D_{sJ}^\star(2860)^+$ is an excellent candidate for the 3^- ($j^P = \frac{5}{2}^-$ or 1^3D_3) $c\bar{s}$.

$D_{sJ}(3040)^+$ is interpreted as the first radially excited 1^+ ($j^P = \frac{1}{2}^+$) D_s meson.

Two 2^- D-wave D_s at 2.70 and 2.81 GeV, and two radially excited D_s around 3.0 GeV are predicted.

However, $D_{sJ}^+(2860)$ used as an input has not been definitely confirmed by other experimental groups. If $D_{sJ}^+(2860)$ does not exist or it is not a $3^-(1^3D_3)$ $c\bar{s}$, our prediction of the spectra of the D wave may change a little. Therefore, more experiments are required to pin down this state.

If the predicted lower spectra is confirmed by experiments in the future, most previous predictions of the spectra deserve reexamination. Lower spectra of the D-wave D_s indicates that there exist unclear features of quark-antiquark potential.

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