PHYSICAL REVIEW D **92,** 034005 (2015)

Combined study of 2*S* and 1*D* open-charm mesons with natural spin-parity

Bing Chen,[1,3,†] Xiang Liu,[2,3,*] and Ailin Zhang[4,‡]

[1]*Department of Physics, Anyang Normal University, Anyang 455000, China*
[2]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[3]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[4]*Department of Physics, Shanghai University, Shanghai 200444, China*

(Received 3 June 2015; revised manuscript received 2 July 2015; published 5 August 2015)

In this paper, we perform a combined study of $2S$ and $1D$ open-charm mesons with natural spin-parity. Our results indicate that $D_1^*(2600)/D_{s1}^*(2700)$ and $D_1^*(2760)/D_{s1}^*(2860)$ are predominantly the 2^3S_1 and 1^3D_1 charmed/charmed-strange mesons, respectively, while $D_3^*(2760)/D_{s3}^*(2860)$ can be regarded as the 1^3D_3 charmed/charmed-strange mesons. In addition, some typical ratios of partial widths of the discussed natural states are predicted, by which future experiments can test these assignments, especially for the $2S$-$1D$ mixing scheme existing in $D_1^*(2600)/D_1^*(2760)$ and $D_{s1}^*(2700)/D_{s1}^*(2860)$.

DOI: 10.1103/PhysRevD.92.034005 PACS numbers: 13.25.Ft, 14.40.Lb

I. INTRODUCTION

Among these hadronic states, the heavy-light mesons, which contain valence heavy quark Q and light antiquark $\bar{q}$, are the special system due to the existence of chiral symmetry and heavy quark dynamics. The investigation of heavy-light mesons can improve our understanding of nonperturbative quantum chromodynamics (QCD).

With experimental progress, more and more heavy-light mesons were reported (see Refs. [1–31]), which can be grouped as the candidates of radial and orbital excitations of heavy-light meson family. In the narrow mass range 2.6–2.9 GeV, there exists an accumulation of a large number of observed charmed and charmed-strange mesons. The information of these states is collected into Table I for the convenience of readers. Before the present paper, the strong decay behaviors of these states have been extensively studied in the context of various models, e.g., the pseudoscalar emission decay model [32], the $^3P_0$ decay model [33–47], the chiral quark model [48–50], the effective Lagrangian approach [51–55], and the EHQ' decay formula [56]. These theoretical works gave a big push to the development of the research of heavy-light meson.

Several experimental measurements of their spin-parity quantum number J^P were performed recently by the LHCb collaboration, i.e., two different D_s states, $D_{s1}^*(2860)$ and $D_{s3}^*(2860)$, were observed in 2014 in the channel of $B_s^0 \to D_{sJ}^{*-}\pi^+ \to \bar{D}^0K^-\pi^+$, where the obtained helicity angle distributions indicate that they are the spin-1 and spin-3 states [30,31]. According to their decay mode of $\bar{D}^0K^-$, they should be the natural parity mesons, which satisfy $P = (-1)^J$. In a word, their spin-parity quantum numbers are 1^- and 3^-, respectively. A spin-1 state, $D_1^*(2760)^0$, was observed in the channel of $B^- \to D_1^{*0}\pi^+ \to D^+\pi^-\pi^+$ [23]. It is a possible D meson with $J^P = 1^-$. Very recently, $D_3^*(2760)^-$ was reported in the process of $B^0 \to D_3^{*-}\pi^+ \to \bar{D}^0\pi^-\pi^+$. Its spin-parity was determined for the first time as $J^P = 3^-$ [24]. The new experimental results provide more abundant information for these states. Until now, four $J^P = 1^-$ states and two $J^P = 3^-$ open-charmed states, which have natural parity, have been established[1] (see Fig. 1). They can be categorized into the $2S$ and $1D$ D and D_s states, where $D_1^*(2600)$, $D_1^*(2760)$, and $D_3^*(2760)$ are the nonstrange partners of $D_{s1}^*(2700)$, $D_{s1}^*(2860)$, and $D_{s3}^*(2860)$, respectively. Their mass gaps reflect the similarity between charmed and charmed-strange meson families well.

These observed $D_1^*(2600)$, $D_1^*(2760)$, and $D_3^*(2760)$ and their strange partners $D_{s1}^*(2700)$, $D_{s1}^*(2860)$, and $D_{s3}^*(2860)$ inspire our interest in carrying out a combined study of $2S$ and $1D$ open-charm mesons with natural spin-parity, which is due to the following reasons:

(1) The corresponding studies of these six open-charmed mesons can be borrowed from each other, which is due to the similarity between charmed and charmed-strange meson families.
(2) The present study is involved in an intriguing issue of $2S$-$1D$ mixing. Rosner discussed the $2S$-$1D$ mixing effect for two charmonia $\psi(3770)$ and $\psi(3686)$ [57]. For these involved open-charmed

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[*] Corresponding author.
xiangliu@lzu.edu.cn
[†] chenbing@shu.edu.cn
[‡] zhangal@staff.shu.edu.cn

[1] The spin-parity quantum number of $D_{s1}^*(2700)$ has been determined as $J^P = 1^-$ by Belle [25] and *BABAR* [26]. According to the mass and decay behaviors, the LHCb collaboration tentatively identified $D_1^*(2600)$ as the $2S(1^-)$ state [22].

TABLE I. The experimental information of these observed charmed and charmed-strange mesons in the mass range 2.6–2.9 GeV [21–31]. Two states marked by † are also named as the corresponding $D_J^*(2650)$ and $D_J(2740)$ in Ref. [22].

State	Production	Observed decays	Mass (MeV)	Width (MeV)	J^P	Year	Collaboration
$D_1^*(2600)^\dagger$	e^+e^-	$D^+\pi^-$, $D^{*+}\pi^-$	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$		2010	*BABAR* [21]
	pp	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$		2013	LHCb [22]
$D(2750)^\dagger$	e^+e^-	$D^{*+}\pi^-$	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$		2010	*BABAR* [21]
	pp	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$		2013	LHCb [22]
$D_1^*(2760)$	$B^- \to D_1^{*0}\pi^+$	$D^+\pi^-$	$2781 \pm 18 \pm 11 \pm 6$	$177 \pm 32 \pm 20 \pm 7$	1^-	2015	LHCb [23]
$D_3^*(2760)$	$B^0 \to D_3^{*-}\pi^+$	$\bar{D}^0\pi^-$	$2800 \pm 7 \pm 5 \pm 4$	$130 \pm 16 \pm 7 \pm 12$	3^-	2015	LHCb [24]
	e^+e^-	$D^+\pi^-$, $D^{*+}\pi^-$	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$		2010	*BABAR* [21]
	pp	$D^{*+}\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$		2013	LHCb [22]
$D_{s1}^*(2700)$	$B^+ \to \bar{D}^0 D_{s1}^{*+}$	D^0K^+	$2708 \pm 9^{+11}_{-10}$	$108 \pm 23^{+36}_{-31}$	1^-	2008	Belle [25]
	$B^{+(0)} \to \bar{D}^0(D^-)D_{s1}^{*+}$	D^0K^+	2699^{+14}_{-7}	127^{+24}_{-19}	1^-	2015	*BABAR* [26]
	e^+e^-	D^0K^+, $D^+K_s^0$	$2688 \pm 4 \pm 4$	$112 \pm 7 \pm 36$		2006	*BABAR* [27]
	e^+e^-	$D^{(*)0}K^+$, $D^{(*)+}K_s^0$	$2710 \pm 2^{+12}_{-7}$	$149 \pm 7^{+39}_{-52}$		2009	*BABAR* [28]
	pp	D^0K^+, $D^+K_s^0$	$2709.2 \pm 1.9 \pm 4.5$	$115.8 \pm 7.3 \pm 12.1$		2012	LHCb [29]
$D_{s1}^*(2860)$	$B_s^0 \to D_{s1}^{*-}\pi^+$	$\bar{D}^0K^-$	$2859 \pm 12 \pm 6 \pm 23$	$159 \pm 23 \pm 27 \pm 72$	1^-	2014	LHCb [30,31]
$D_{s3}^*(2860)$	$B_s^0 \to D_{s3}^{*-}\pi^+$	$\bar{D}^0K^-$	$2860.5 \pm 2.6 \pm 2.5 \pm 6.0$	$53 \pm 7 \pm 4 \pm 6$	3^-	2014	LHCb [30,31]
	e^+e^-	D^0K^+, $D^+K_s^0$	$2856.6 \pm 1.5 \pm 5.0$	$48 \pm 7 \pm 10$		2006	*BABAR* [27]
	e^+e^-	$D^{(*)0}K^+$, $D^{(*)+}K_s^0$	$2862 \pm 2^{+5}_{-2}$	$48 \pm 3 \pm 6$		2009	*BABAR* [28]
	pp	D^0K^+, $D^+K_s^0$	$2866.1 \pm 1.0 \pm 6.3$	$69.9 \pm 3.2 \pm 6.6$		2012	LHCb [29]

mesons in this paper, there should also exist 2S-1D mixing when studying $D_1^*(2600)/D_1^*(2760)$ and $D_{s1}^*(2700)/D_{s1}^*(2860)$.

(3) Besides giving the discussion of 2S-1D mixing effect existing in these 2S and 1D open-charm mesons, the main task of this paper is to establish 2S and 1D open-charm mesons with natural spin-parity, which is also helpful to test whether there exists the spin-orbit inversion in the heavy-light mesons [58,59] or not [60]. Before giving a definite answer, it is obvious that establishing the 2S and 1D open-charm mesons with natural spin-parity is a key step.

Just considering the present update experimental status of 2S and 1D open-charm mesons with natural spin-parity and the importance of studying them just mentioned above, in this paper, we are dedicated to this interested research topic by considering $D_1^*(2600)$, $D_1^*(2760)$, and $D_3^*(2760)$ and their strange partners $D_{s1}^*(2700)$, $D_{s1}^*(2860)$, and $D_{s3}^*(2860)$, where we mainly focus on their two-body Okubo-Zweig-Iizuka allowed strong decay behaviors, which can provide valuable information of their features including partial and total decay widths. For calculating these decays, the Eichten-Hill-Quigg (EHQ) decay formula [61] is adopted in this paper, which is an effective approach to deal with the strong decay calculation involved in the open-charm meson [61].

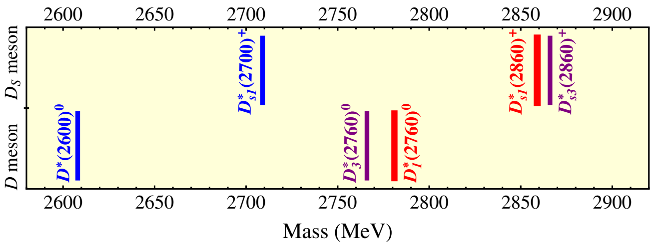

FIG. 1 (color online). $D_1^*(2600)$, $D_1^*(2760)$, and $D_3^*(2760)$ and the corresponding strange partners $D_{s1}^*(2700)$, $D_{s1}^*(2860)$, and $D_{s3}^*(2860)$.

The manuscript is arranged as follows. In Sec. II, we first give a brief introduction to the EHQ' formula. Then, we give the further phenomenological analysis combined with the present experimental data. In Sec. III, the paper ends with the discussion and conclusion.

II. THE DECAY BEHAVIORS OF THE DISCUSSED 2S AND 1D OPEN-CHARM MESONS WITH NATURAL SPIN-PARITY

A. EHQ' decay formula

As an approximate symmetry existing in the heavy-light meson system, the heavy quark symmetry (HQS) plays an important role in the dynamics of the heavy-light meson. In the HQS limit ($m_Q \to \infty$), only the light component of a heavy-light meson takes an active part in the strong decays [62]. Under this consideration, two heavy-light mesons, with the same light degrees of freedom j_q, but different total angular momentum J, shall have the similar decay properties. In general, these two states can be grouped in one doublet. This picture is supported by the available properties of P-wave heavy-light mesons [63].

TABLE II. The values of $\mathcal{C}^{s_Q,j'_q,J'}_{j_h,J,j_q}$ for the different decay modes of these discussed open-charm mesons with the 2^3S_1, 1^3D_1, and 1^3D_3 quantum numbers. Here, $\mathcal{P}$ and $\mathcal{V}$ in the first row denote the light pseudoscalar and vector mesons, respectively. In addition, s, p, d, f, and g in the brackets represent that the corresponding decays occur via S-wave, P-wave, D-wave, F-wave, and G-wave, respectively.

$nL(J^P)$	$1S(0^-)+\mathcal{P}$	$1S(1^-)+\mathcal{P}$	$1S(0^-)+\mathcal{V}$	$1P(1^+,1/2)+\mathcal{P}$	$1P(1^+,3/2)+\mathcal{P}$	$1P(2^+)+\mathcal{P}$	$2S(0^-)+\mathcal{P}$
2^3S_1	$\sqrt{1/3}(p)$	$-\sqrt{2/3}(p)$	$\sqrt{1/3}(p)$	$1\ (s)$	$\sqrt{1/2}\ (d)$	$-\sqrt{3}/2\ (d)$	
1^3D_1	$-\sqrt{2/3}(p)$	$-\sqrt{1/3}(p)$	$-\sqrt{2/3}(p)$	$1\ (d)$	$-1\ (s), -\sqrt{1/2}\ (d)$	$-\sqrt{1/2}\ (d)$	$-\sqrt{2/3}(p)$
1^3D_3	$\sqrt{3/7}(f)$	$-\sqrt{4/7}(f)$	$\sqrt{3/7}(f)$	$-\sqrt{4/7}(d)$	$\sqrt{1/7}(d), \sqrt{9/14}\ (g)$	$-\sqrt{6/7}\ (d), -\sqrt{5/14}\ (g)$	$\sqrt{3/7}(f)$

Based on this picture mentioned above, a decay formula which depicts the transition between two heavy-light mesons was proposed by Eichten, Hill, and Quigg in Ref. [61], which is also called as the EHQ' formula, i.e.,

$$\Gamma^{H\to H'h}_{j_h,\ell} = \xi\left(\mathcal{C}^{s_Q,j'_q,J'}_{j_h,J,j_q}\right)^2 \left|\mathcal{M}^{j_q,j'_q}_{j_h,\ell}(q/\beta)\right|^2 q e^{-q^2/(6\beta^2)}, \qquad (1)$$

where ξ is the flavor factor which can be found in Ref. [64]. $q = |\vec{q}|$ denotes the three-momentum of the final state in the rest frame of the initial state. H and H' represent the initial and final heavy-light mesons, respectively. h denotes the light flavor meson. In addition, $\mathcal{C}^{s_Q,j'_q,J'}_{j_h,J,j_q}$ is a normalized coefficient, which satisfies the following relation:

$$\mathcal{C}^{s_Q,j'_q,J'}_{j_h,J,j_q} = \sqrt{(2J'+1)(2j_q+1)}\begin{Bmatrix} s_Q & j'_q & J' \\ j_h & J & j_q \end{Bmatrix}, \qquad (2)$$

where $\vec{j}_h \equiv \vec{s}_h + \vec{\ell}$. The symbols s_h and ℓ represent the spin of the light meson h and the orbital angular momentum relative to H', respectively. The transition factors $\mathcal{M}^{j_q,j'_q}_{j_h,\ell}(p/\beta)$ which involve the concrete dynamics can be calculated by phenomenological models, like the relativistic chiral quark model [65] and the $^3P_0$ model [56,66]. Equation (2) reflects the requirement of HQS. Until now, the EHQ' formula has been applied to study open-charm mesons [56,64,66] and excited heavy baryons [67].

For the 2S and 1D open-charm mesons with natural spin-parity, the relevant values of $\mathcal{C}^{s_Q,j'_q,J'}_{j_h,J,j_q}$ and the expressions of the corresponding transition factors are listed in Tables II and III, respectively. These transition factors are determined by the $^3P_0$ model. Thus, two parameters β and γ are introduced in our calculation. Here, β is the scale of harmonic oscillator wave function depicting the mesons in the discussed transitions.[2] Following Ref. [56], we take $\beta = 0.38$ GeV. The parameter γ denotes the strength of quark pair creation from vacuum. In this paper, we assume that the charmed and charmed-strange mesons are governed by a same γ. As shown in our previous paper [64], all P-wave heavy-light mesons were explained well in the framework of the EHQ' formula, where γ is directly fixed by the width of $D_2^*(2460)^0$, i.e., $D_2^*(2460)^0$ is a 1^3P_2 D state [63]. Its mass and width are 2460.47 ± 0.14 MeV and 47.7 ± 0.7 MeV, respectively [69]. Via Eq. (3), we determine $\gamma = 0.125$. In the following, we will apply the EHQ' formula with these determined parameters to calculate the decay behaviors of 2S and 1D open-charm mesons with natural spin-parity, which is the main task of present paper. Finally, it needs to be emphasized that we adopt experimental average values for the masses of these discussed 2S and 1D open-charm mesons with natural spin-parity. For other open-charm mesons and light flavor mesons involved in calculation, the corresponding masses are taken from Particle Data Group (PDG) [63].

TABLE III. The transition factors $\mathcal{M}^{j_q,j'_q}_{j_h,l}(p/\beta)$ for different decay channels of the discussed 2^3S_1, 1^3D_1, and 1^3D_3 open-charm mesons. Here, we define $\mathcal{G} = 32\pi^{1/4}\gamma/(9\beta^{1/2})$.

$n^{2S+1}L_J \to n'L'(j'^{P'}_{\ell}) + \mathcal{H}$	$\mathcal{M}^{j_q,j'_q}_{j_h,\ell}(p/\beta)$
$2^3S_1 \to 1S(\frac{1}{2}^-) + 0^-$	$-\mathcal{G}\frac{5}{3^2}\frac{q}{\beta}(1-\frac{2}{15}\frac{q^2}{\beta^2})$
$2^3S_1 \to 1S(\frac{1}{2}^-) + 1^-$	$-\mathcal{G}\frac{2^{1/2}\cdot 5}{3^2}\frac{q}{\beta}(1-\frac{2}{15}\frac{q^2}{\beta^2})$
$2^3S_1 \to 1P(\frac{1}{2}^+) + 0^-$	$-\mathcal{G}\frac{1}{2^{1/2}\cdot 3^{3/2}}(1-\frac{7}{9}\frac{q^2}{\beta^2}+\frac{2}{27}\frac{q^4}{\beta^4})$
$2^3S_1 \to 1P(\frac{3}{2}^+) + 0^-$	$\mathcal{G}\frac{13}{3^{7/2}}\frac{q^2}{\beta^2}(1-\frac{2}{39}\frac{q^2}{\beta^2})$
$1^3D_1 \to 1S(\frac{1}{2}^-) + 0^-$	$\mathcal{G}\frac{5^{1/2}\cdot 2^{1/2}}{3^2}\frac{q}{\beta}(1-\frac{2}{15}\frac{q^2}{\beta^2})$
$1^3D_1 \to 1S(\frac{1}{2}^-) + 1^-$	$-\mathcal{G}\frac{2^{1/2}}{3^2}\frac{q}{\beta}(1-\frac{2}{15}\frac{q^2}{\beta^2})$
$1^3D_1 \to 1P(\frac{1}{2}^+) + 0^-$	$\mathcal{G}\frac{5^{1/2}}{3^{7/2}}\frac{q^2}{\beta^2}(1+\frac{1}{9}\frac{q^2}{\beta^2})$
$1^3D_1 \to 1P(\frac{3}{2}^+) + 0^-$	$-\mathcal{G}\frac{2\cdot 5^{1/2}}{3^{3/2}}(1-\frac{5}{18}\frac{q^2}{\beta^2}+\frac{1}{135}\frac{q^4}{\beta^4})$ $-\mathcal{G}\frac{13}{3^{7/2}\cdot 5^{1/2}}\frac{q^2}{\beta^2}(1-\frac{2}{39}\frac{q^2}{\beta^2})$
$1^3D_1 \to 2S(\frac{1}{2}^-) + 0^-$	$\mathcal{G}\frac{5^{1/2}}{3^{7/2}}\frac{q}{\beta}(1-\frac{29}{30}\frac{q^2}{\beta^2}+\frac{1}{45}\frac{q^4}{\beta^4})$
$1^3D_3 \to 1S(\frac{1}{2}^-) + 0^-$	$-\mathcal{G}\frac{2^{3/2}}{3^3\cdot 5^{1/2}}\frac{1}{\beta^3}$
$1^3D_3 \to 1S(\frac{1}{2}^-) + 1^-$	$\mathcal{G}\frac{29^{1/2}}{3^3\cdot 5}\frac{1}{\beta^3}$
$1^3D_3 \to 1P(\frac{1}{2}^+) + 0^-$	$-\mathcal{G}\frac{2\cdot 5^{1/2}}{3^{7/2}}\frac{1}{\beta^2}(1-\frac{1}{15}\frac{q^2}{\beta^2})$
$1^3D_3 \to 1P(\frac{3}{2}^+) + 0^-$	$\mathcal{G}\frac{2^{5/2}\cdot 7^{1/2}}{3^{7/2}\cdot 5^{1/2}}\frac{1}{\beta^2}(1-\frac{1}{42}\frac{q^2}{\beta^2})$ $\mathcal{G}\frac{2^2}{3^4\cdot 5^{1/2}\cdot 7^{1/2}}\frac{1}{\beta^4}$
$1^3D_3 \to 2S(\frac{1}{2}^-) + 0^-$	$\mathcal{G}\frac{2^2}{3^{5/2}\cdot 5^{1/2}}\frac{1}{\beta^3}(1-\frac{1}{36}\frac{q^2}{\beta^2})$

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[2] According to the results in Ref. [68], we adopt a universal β value for the mesons involved in the discussed transitions.

B. $D_1^*(2600)$, $D_{s1}^*(2700)$, $D_1^*(2760)$ and $D_{s1}^*(2860)$ as pure states

First, we discuss $D_1^*(2600)$, $D_{s1}^*(2700)$, $D_1^*(2760)$ and $D_{s1}^*(2860)$ without introducing $2S$-$1D$ mixing, where their partial and total decay widths are collected in Tables IV and V (see the results corresponding to mixing angle $\phi = 0^\circ$).

With the 2^3S_1 assignment, the total decay width of $D_1^*(2600)$ is predicted as 204.6 MeV, which is larger than the averaged value of widths measured by *BABAR* [21] and LHCb [22], but is close to the upper limit of the measurement by LHCb [22] (see Table IV). We also predict the branching ratio

$$\frac{\mathcal{B}(D_1^*(2600) \to D\pi)}{\mathcal{B}(D_1^*(2600) \to D^*\pi)} = 0.53, \qquad (3)$$

which is close to the upper limit of the *BABAR* result (0.21–0.43) [21]. It is obvious that the main feature of $D_1^*(2600)$ can be understood under the 2^3S_1 assignment.

If $D_{s1}^*(2700)$ is the strange partner of $D_1^*(2600)$, the predicted width can reach up to 209.8 MeV which is near to the upper limit of the *BABAR* result [28] (see Table V). Furthermore, the predicted branching ratio is

$$\frac{\mathcal{B}(D_{s1}^*(2700) \to D^*K)}{\mathcal{B}(D_{s1}^*(2700) \to DK)} = 1.43, \qquad (4)$$

which is close to the upper limit of the *BABAR* result (0.66–1.16) [28]. The above facts indicate that $D_{s1}^*(2700)$ has a dominant 2^3S_1 component.

As a 1^3D_1 state, the calculated total decay width of $D_1^*(2760)$ is around 300 MeV. Before this paper, the studies in Refs. [44,45,47,48] also suggested that the decay width of the 1^3D_1 D state should be large. We list the theoretical and experimental results in Fig. 2 for the comparison. Among these allowed decay modes, the channels of $D\pi$, $D^*\pi$ and $D_1(2420)\pi$ are important for $D_1^*(2760)$ due to large partial widths, e.g., the channel of $D_1(2420)\pi$ with branching ratio 65.9% is its dominant decay mode. The same conclusion has been obtained in Refs. [44,45,47,48]. As a 1^3D_1 state, the below ratio,

TABLE IV. Decay widths of $D_1^*(2600)$ and $D_1^*(2760)$ with several typical ϕ mixing angles (in MeV).

	$D_1^*(2600)$					$D_1^*(2760)$				
Decay channels	-30°	-15°	0°	15°	30°	-30°	-15°	0°	15°	30°
$D\pi$	107.2	89.2	62.2	33.6	10.9	3.7	18.0	39.4	62.1	80.0
$D^*\pi$	48.3	84.5	116.9	136.7	138.7	96.9	58.7	24.6	3.7	1.6
D_sK	11.9	9.9	6.9	3.7	1.2	0.9	4.4	9.6	15.1	19.5
D_s^*K	0.0	0.4	1.0	1.7	2.4	11.7	7.1	3.0	0.5	0.2
$D\eta$	16.2	13.5	9.4	5.1	1.7	0.9	4.6	10.0	15.8	20.3
$D^*\eta$	2.2	3.9	5.3	6.2	6.2	15.7	9.5	4.0	0.6	0.2
$D\rho$	⋯	⋯	⋯	⋯	⋯	42.1	21.5	6.1	0.0	4.9
$D\omega$	⋯	⋯	⋯	⋯	⋯	13.2	6.7	1.9	0.0	1.6
$D_1'(2430)\pi$	2.1	2.6	2.8	2.6	2.1	1.6	1.0	0.4	0.1	0.0
$D_1(2420)\pi$	37.1	11.0	0.1	7.3	30.8	121.4	165.5	191.4	192.1	167.5
$D_2^*(2460)\pi$	0.0	0.0	0.0	0.0	0.0	1.1	0.4	0.0	0.1	0.5
$D(2550)\pi$	⋯	⋯	⋯	⋯	⋯	0.0	0.1	0.1	0.2	0.3
Total	225.0	215.0	204.6	196.9	194.0	309.2	297.5	290.4	290.3	296.6
Experiment	104.5–175.9 [22]					118–236 [23]				

TABLE V. Decay widths of $D_{s1}^*(2700)$ and $D_{s1}^*(2860)$ with several typical ϕ mixing angles (in MeV).

	$D_{s1}^*(2700)$					$D_{s1}^*(2860)$				
Decay channels	-30°	-15°	0°	15°	30°	-30°	-15°	0°	15°	30°
DK	140.9	117.2	81.7	44.1	14.3	5.7	27.6	60.4	95.2	122.7
D^*K	46.7	81.8	113.1	132.3	134.3	130.3	79.0	33.1	5.0	2.1
$D_s\eta$	20.2	16.6	11.3	5.7	1.3	1.3	6.1	13.3	21.0	27.0
$D_s^*\eta$	1.6	2.7	3.7	4.3	4.3	18.9	11.5	4.8	0.7	0.3
DK^*	⋯	⋯	⋯	⋯	⋯	42.3	21.6	6.1	0.0	5.0
Total	209.4	218.3	209.8	186.4	154.2	198.5	145.8	117.7	121.9	157.1
Experiment	103–195 [28]					$159 \pm 23 \pm 27 \pm 72$ [30,31]				

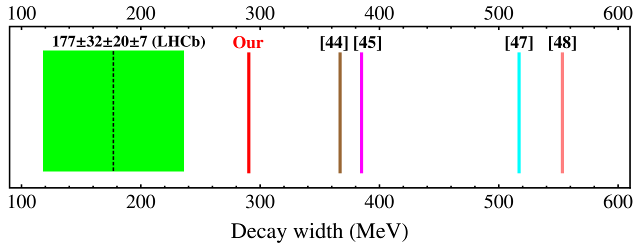

FIG. 2 (color online). A comparison of the experimental [23] and theoretical widths [44,45,47,48] for the $D_1^*(2760)$ with the $D(1^3D_1)$ assignment.

$$\frac{\mathcal{B}(D_1^*(2760)\to D\pi)}{\mathcal{B}(D_1(2760)\to D^*\pi)}=1.60, \tag{5}$$

is predicted for $D_1^*(2760)$, which is consistent with the results in Refs. [44,45,47,48] (see Table VI).

As the strange partner of $D_1^*(2760)$, the total decay width of $D_{s1}^*(2860)$ is around 117.7 MeV, which is consistent with the measurement given by LHCb [30,31] and comparable with former results in Refs. [32–35] (see Table VII). Our results also show that the DK mode is one of the main decay channels, which can explain why $D_{s1}^*(2860)$ was first found in its DK channel [30,31]. Additionally, we obtain the ratio

$$\frac{\mathcal{B}(D_{s1}^*(2860)\to DK)}{\mathcal{B}(D_{s1}^*(2860)\to D^*K)}=1.82, \tag{6}$$

which is close to 1.92 given by Ref. [34] and 1.42 by Ref. [35].

In this subsection, we mainly focus on $D_1^*(2600)$, $D_{s1}^*(2700)$, $D_1^*(2760)$ and $D_{s1}^*(2860)$ as pure states and give the phenomenological analysis, where the information of their other decay channels can be found in Tables IV–V. In fact, there should exist a 2S-1D mixing effect to these discussed $D^*(2600)$, $D_{s1}^*(2700)$, $D_1^*(2760)$ and $D_{s1}^*(2860)$, which will be illustrated in the next subsection.

TABLE VI. Comparison of different theoretical results for the ratio of $\mathcal{B}(D_1^*(2760)\to D\pi)/\mathcal{B}(D_1(2760)\to D^*\pi)$.

Ref. [44]	Ref. [45]	Ref. [47]	Ref. [48]	Our
2.04	2.17	1.62	2.42	1.60

TABLE VII. Comparison of different theoretical results for the decay width of $D_{s1}^*(2860)$ (in MeV).

Ref. [32]	Ref. [33]	Ref. [34]	Ref. [35]	Our
145	132	186.8	153.2	117

C. $D_1^*(2600)$ and $D_{s1}^*(2700)$ as orthogonal partners of $D_1^*(2760)$ and $D_{s1}^*(2860)$ respectively

In reality, $D_1^*(2600)$ should be the orthogonal partner of $D_1^*(2760)$. There also exists the similar relation for their strange partners $D_{s1}^*(2700)$ and $D_{s1}^*(2860)$. Thus, we need to investigate the 2S-1D mixing effect, where the mixing scheme satisfies [36]

$$\begin{pmatrix} |(SD)_1\rangle_L \\ |(SD)_1\rangle_H \end{pmatrix}=\begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix}\begin{pmatrix} |2^3S_1\rangle \\ |1^3D_1\rangle \end{pmatrix} \tag{7}$$

with ϕ as the mixing angle. The states marked by subscripts L and H are identified as the low-mass and high-mass mixed states, respectively. For discussing the 2S-1D mixing effect, we take several typical ϕ values, i.e., $\phi=-30^\circ$, -15°, 15°, and 30°. The corresponding partial and total widths of $D_1^*(2600)$, $D_{s1}^*(2700)$, $D_1^*(2760)$ and $D_{s1}^*(2860)$ are shown in Tables IV–V. Our results indicate that there exists dependence of the total widths of $D_1^*(2600)$, $D_{s1}^*(2700)$, and $D_1^*(2760)$ on the mixing angle ϕ. The width of $D_{s1}^*(2860)$ highly depends on ϕ.

We notice that the ratios of partial decay widths are good physical quantities to constrain the mixing angle ϕ. At present, *BABAR* [21,28] measured ratios

$$\frac{\mathcal{B}(D_1^*(2600)\to D\pi)}{\mathcal{B}(D_1^*(2600)\to D^*\pi)}=0.32\pm0.02\pm0.09, \tag{8}$$

and

$$\frac{\mathcal{B}(D_{s1}^*(2700)\to D^*K)}{\mathcal{B}(D_{s1}^*(2700)\to DK)}=0.91\pm0.13\pm0.12. \tag{9}$$

If fitting these two ratios, the mixing angles $\phi=4^\circ$–17° and $\phi=-4^\circ$ to $-16^\circ$are obtained for $D_1^*(2600)$ and $D_{s1}^*(2700)$, respectively, which show that our results by the EHQ' formula favor small mixing angle.

Besides the $D^{(*)}\pi$ and $D^{(*)}K$ modes, the $D_{(s)}\eta$ and D_sK channels are also important to reflect the features of these discussed open-charm mesons. Furthermore, we get the following ratios:

$$\frac{\mathcal{B}(D_1^*(2600)\to D\eta)}{\mathcal{B}(D_1^*(2600)\to D\pi)}=0.15,$$
$$\frac{\mathcal{B}(D_1^*(2600)\to D_sK)}{\mathcal{B}(D_1^*(2600)\to D\pi)}=0.11,$$
$$\frac{\mathcal{B}(D_{s1}^*(2700)\to D_s\eta)}{\mathcal{B}(D_{s1}^*(2700)\to DK)}=0.14,$$
$$\frac{\mathcal{B}(D_{s1}^*(2860)\to D_s\eta)}{\mathcal{B}(D_{s1}^*(2860)\to DK)}=0.22.$$

We need to specify that these four ratios are weakly dependent on the mixing angle, and independent on the parameter γ.

If the $2S$-$1D$ mixing effect exists, $D_1^*(2760)/D_{s1}^*(2860)$ should be the orthogonal partner of $D_1^*(2600)/D_{s1}^*(2700)$. With the ranges of mixing angle obtained above, we predict

$$\frac{\mathcal{B}(D_1^*(2760) \to D\pi)}{\mathcal{B}(D_1^*(2760) \to D^*\pi)} = 2.62\text{–}28.86, \qquad (10)$$

and

$$\frac{\mathcal{B}(D_{s1}^*(2860) \to D^*K)}{\mathcal{B}(D_{s1}^*(2860) \to DK)} = 0.31\text{–}1.16, \qquad (11)$$

which are different from the results in Eqs. (5) and (6), respectively. These results can be also applied to test the $2S$-$1D$ mixing effect.

D. $D_3^*(2760)$ and $D_{s3}^*(2860)$

In the following, the phenomenological analysis of two 3^- open-charm mesons $D_3^*(2760)$ and $D_{s3}^*(2860)$ is given. The corresponding partial and total widths are shown in Table VIII.

Under the $D(1^3D_3)$ assignment, the predicted widths of $D_3^*(2760)$ is about 49.7 MeV, which is comparable with the experimental data reported by *BABAR* [21] and LHCb [22]. The results of Refs. [44–46,48,56] also supported $D_3^*(2760)$ as the $D(1^3D_3)$ state.

We notice a new result of $D_3^*(2760)$ released by LHCb very recently [24], where the averaged width from two models (the Isobar and K-matrix formalisms) is [24]

$$\Gamma(D_3^*(2760)) = 130 \pm 16 \pm 7 \pm 12 \text{ MeV},$$

which is far larger than the present theoretical results [44–46,48,56] and former experimental data [21,22]. Additionally, the mass of $D_3^*(2760)$ in Ref. [24] is about 40 MeV higher than previous experimental data (see Table I for more details). We list the experimental and theoretical widths in Fig. 3 for a comparison. The theoretical results favor the experimental measurements from *BABAR* and LHCb [21,22]. The LHCb collaboration may overestimate the width of $D_3^*(2760)$ in the latest measurement [24]. In the near future, more precise measurement of the resonant parameter of $D_3^*(2760)$ is crucial to clarify this mess. The possible explanation for the change of the new result of $D_3^*(2760)$ given by LHCb [24] will be presented in the next section.

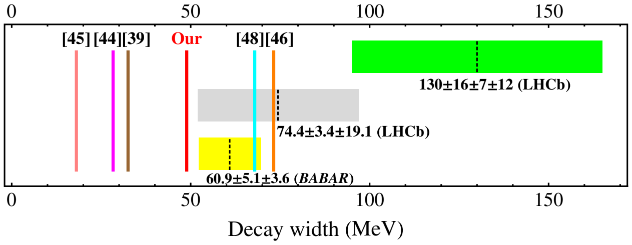

FIG. 3 (color online). A comparison of the experimental [21,22,24] and theoretical widths [39,44–46,48] for the $D_3^*(2760)$ with the $D(1^3D_3)$ assignment.

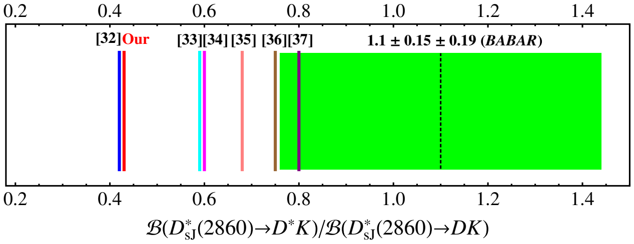

FIG. 4 (color online). A comparison of the experimental [28] and theoretical results [32–37] for the ratio $\mathcal{B}(D_{sJ}^*(2860) \to D^*K)/\mathcal{B}(D_{sJ}^*(2860) \to DK)$.

TABLE VIII. The partial and total widths of $D_3^*(2760)$ and $D_{s3}^*(2860)$ as $D(1^3D_3)$ and $D_s(1^3D_3)$, respectively.

$D_3^*(2760)$				$D_{s3}^*(2860)$	
Modes	Γ_i (MeV)	Modes	Γ_i (MeV)	Modes	Γ_i (MeV)
$D\pi$	27.9	$D\rho$	0.2	DK	28.5
D_sK	1.6	$D\omega$	0.1	D^*K	12.2
$D^*\pi$	15.5	$D_1'(2430)\pi$	1.1	$D_s\eta$	1.9
D_s^*K	0.2	$D_1(2420)\pi$	0.4	$D_s^*\eta$	0.4
$D\eta$	1.4	$D_2^*(2460)\pi$	1.1	DK^*	0.2
$D^*\eta$	0.2	$D(2550)\pi$	0.0		
		Total	49.7	Total	43.2

With the $D_s(1^3D_3)$ assignment, we show the decay behavior of $D_{s3}^*(2860)$ in Table VIII, where the calculated total decay width is about 43.2 MeV, which is in good agreement with the experimental data [27–31] (see Table I) and comparable with other theoretical results obtained by different phenomenological models [32–37], where the width of the $D_s(1^3D_3)$ state was predicted in the range of 14–85 MeV. However, we also notice that most predicted values for ratio $\mathcal{B}(D_s^*(1^3D_3) \to D^*K)/\mathcal{B}(D_s^*(1^3D_3) \to DK)$ are smaller than the *BABAR* measurement [28] (see Fig. 4). This discrepancy between theoretical and experimental results should be clarified by further experimental and theoretical efforts. In the next section, we will give some discussions for this point.

III. DISCUSSION AND CONCLUSION

In this paper, we carried out a combined study of $2S$ and $1D$ open-charm mesons with natural spin-parity, which was mainly inspired by the recent new experimental progresses on open-charm mesons reported by LHCb [23,24,30,31]. Our study is helpful to identify the properties of these observed $2S$ and $1D$ open-charm mesons with natural spin-parity. Besides comparing our results with the present data, we also gave some typical ratios of partial decay widths and partial decay widths, which are crucial information to establish $2S$ and $1D$ open-charm mesons with natural spin-parity. In addition, the $2S$-$1D$ mixing effect existing

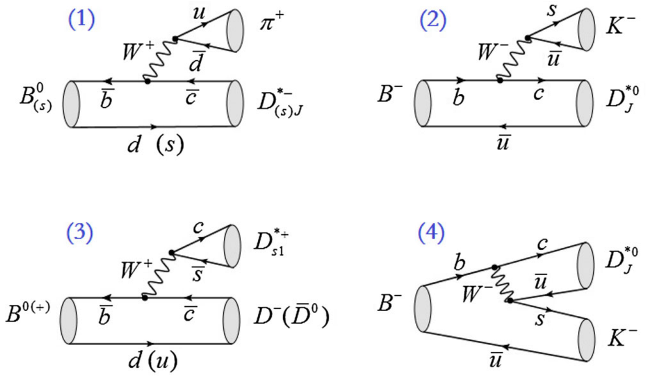

FIG. 5 (color online). The topological diagrams for the productions of excited D and D_s mesons via the nonleptonic decays of $B_{(s)}$ mesons.

in these 2S and 1D open-charm mesons with natural spin-parity was discussed, which is an interested research topic for the experiments in the future.

Before closing this paper, we still want to give more discussions relevant to these 2S and 1D open-charm mesons with natural spin-parity. Checking these collected experimental data in Table I, we notice that the measurements of the resonant parameter for the same state by different experiments are different from each other. Thus, the present crucial task for experiment is to precisely measure the resonant parameters of these 2S and 1D open-charm mesons with natural spin-parity. With more experimental data collected by LHCb and forthcoming Belle II, we believe that experiments will make more progress on this point.

In Fig. 5, we present the possible topological diagrams relevant to the productions of these discussed open-charm mesons through the nonleptonic decays of $B_{(s)}$ mesons. Two states, $D^*_{s1}(2860)^-$ and $D^*_{s3}(2860)^-$, were observed in the process depicted in Fig. 5 (1). With the same topological diagram, however, only $D^*_3(2760)^-$ was reported by LHCb. In fact, there does not exist any suppression to the $D^*_1(2760)$ state produced via Fig. 5 (1), where the total angle momentum of $D^{*-}_1(2760)$ is smaller than that of $D^*_3(2760)^-$. In Ref. [24], LHCb admitted that "The current analysis does not preclude a charged spin-1 D^* state at around the same mass." Thus, there exists the possibility that the $D^*_3(2760)^-$ structure reported by LHCb might be from a superposition of 1^- and a 3^- 1D-wave charmed mesons, which provides a possible explanation of why the experimental width of $D^*_3(2760)^-$ by LHCb [24] is obviously larger than former measurements by the e^+e^- and pp collisions [21,22].

By $B^- \to D^{*0}_J(D^+\pi^-)K^-$ corresponding to Fig. 5 (2) and (4), where the later one is a color-suppressed process, LHCb has reported the signal of $D^*_1(2760)^0$, where $D^*_3(2760)^0$ is missing. According to the experience of the observations of $D^*_{s1}(2860)$ and $D^*_{s3}(2860)$ in $B^0_s \to \bar{D}^0K^-\pi^+$ via Fig. 5 (1), there probably exists a $D^*_3(2760)^0$ signal associated with $D^*_1(2760)^0$ in $B^- \to D^+\pi^-K^-$ since Fig. 5 (2) has the same topological structure as that of Fig. 5 (1).

As shown in Tables IV and VI, the $D_1(2420)\pi$ mode is an important decay channel for $D^*_1(2760)$, but a subordinate channel for $D^*_3(2760)$. Thus, we suggest the experiment to carry out the analysis of $B^0 \to D^*_1(2760)^-\pi^+ \to D_1(2420)^0\pi^-\pi^+$ and $B^- \to D^*_1(2760)^0K^- \to D_1(2420)^+\pi^-K^-$, by which the $D^*_1(2760)$ signal can be easily disentangled from the $D^*_3(2760)$ signal since the $D^*_3(2760)$ signal is suppressed here.

As illustrated in Sec. II, the experimental data of ratio $\mathcal{B}(D^*K)/\mathcal{B}(DK)$ of $D^*_{s3}(2860)$ is larger than most theoretical results [32–37,51]. The nonstrange partner of $D^*_{s3}(2860)$ corresponds to $D^*_3(2760)$. We notice that there exists a possible 2^- state $D_2(2750)$ [22] (see Table I for more details). Due to the similarity between charmed and charmed-strange meson families, we conjugate the existence of a 2^- state with similar mass to that of $D^*_{s3}(2860)$. At present, it is difficult to exclude the possibility that the present $D^*_{s3}(2860)$ signal in the D^*K invariant mass spectrum [28] contains a $D_s(2^-)$ structure. If it is true, the discrepancy between theoretical and experimental results can be understood well for the ratio $\mathcal{B}(D^*K)/\mathcal{B}(DK)$ of $D^*_{s3}(2860)$ [52,56], i.e., $\mathcal{B}(D^*K)/\mathcal{B}(DK)$ of $D^*_{s3}(2860)$ is overestimated probably.

It is not the end of the story of the study of 2S and 1D open-charm mesons with natural spin-parity, since there still exist some puzzles just discussed above, which are waiting for the solutions given by the joint effort from experimentalists and theorists.

ACKNOWLEDGMENTS

B. C. would like to thank the Academic Exchange Platform of Theoretical Physics (Lanzhou University) for supporting his stay at Lanzhou University. This project is supported by the National Natural Science Foundation of China under Grants No. 11305003, No. 11222547, No. 11175073, No. 11447604 and No. 11475111, the Key Program of the He'nan Educational Committee of China under Grant No. 13A140014, the Ministry of Education of China (SRFDP under Grant No. 20120211110000), and the Fok Ying Tung Education Foundation (Grant No. 131006), and the Innovation Program of Shanghai Municipal Education Commission under Grant No. 13ZZ066.

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